

The Impact Clock Hypothesis: Asteroid Reset Windows and the Stone-Age Galaxy

Douglas. C. Youvan

doug@youvan.com

www.youvan.ai

December 3, 2025

Over cosmic time, planets like Earth are bombarded by objects whose energies span many orders of magnitude, from harmless fireballs to Chicxulub-class strikes that restructure entire biospheres. Civilizations arise, if they arise at all, on worlds that live under this stochastic rain. Most discussions of the Fermi Paradox implicitly assume that once a technological civilization appears, it enjoys a long, relatively stable window in which to build radio telescopes, launch probes, and perhaps expand into space. This paper explores a more precarious picture: what if the “impact clock” on Earth-like planets routinely knocks advanced societies back to pre-industrial or even stone-age conditions, without extinguishing their species? The central claim is not that asteroid impacts are the only Great Filter, but that they create recurrent, civilization-scale reset windows that sharply shorten the average radio-loud and spacefaring phase. Using the five-million-to-one energy contrast between a 20 megaton city-killer and a 10^8 megaton Chicxulub-class impact as a scaling anchor, we develop a simple dynamical model of planetary history with three interacting clocks: the impact clock, the technological ascent clock, and the escape clock (time to become genuinely multi-planetary). We then ask: in a galaxy filled with such worlds, what fraction of civilizations are likely to be “on the air” at any given moment, and how many are trapped in cycles of rise, collapse, and mythologized memory?

Keywords: Fermi Paradox, Great Filter, asteroid impacts, impact clock, civilization reset, Chicxulub, megaton scaling, radio-loud window, stone-age survivors, planetary defense, global catastrophic risk.

A collaboration with GPT-5.1-Thinking-Extended. 57 pages. CC4.0.

Outline

1. Introduction: From Impact Craters to a Stone-Age Galaxy

- 1.1 The Fermi question, narrowed to peer-level technological civilizations
- 1.2 Why recurrent natural resets matter more than one-off catastrophes
- 1.3 Three clocks on an inhabited planet: impact, ascent, and escape
- 1.4 Overview of the impact clock hypothesis and the structure of the argument

2. Energy and Fragility: What It Takes to Erase a Civilization

- 2.1 Megatons as a common currency for bombs, earthquakes, and impacts
- 2.2 The five-million-to-one contrast: 20 megatons versus 10^8 megatons
- 2.3 Thresholds: from regional disaster to global infrastructural collapse
- 2.4 Destroying cities without destroying species: the reset regime

3. Impact Climatology: Recurrence Rates on Earth-like Worlds

- 3.1 The size–frequency distribution of impactors
- 3.2 Recurrence times for Tunguska-class, city-killer, and sub-Chicxulub events
- 3.3 Chicxulub-scale events as biosphere filters, not just civilization filters
- 3.4 Variability across planetary systems: thick tails and unlucky worlds

4. The Technological Ascent Clock

- 4.1 From fire to radio: sketching a minimal technological pathway
- 4.2 Plausible timescales for industrialization and global networking
- 4.3 Cultural and environmental contingencies on ascent speed
- 4.4 How often does a species “get close” without fully converging on our trajectory?

5. The Escape Clock: Time to Multi-Planetary Robustness

- 5.1 Defining “escape”: off-world industry, self-sustaining colonies, or probes
- 5.2 Engineering constraints: launch windows, energy budgets, and materials
- 5.3 Social and political constraints: coordination, risk appetite, and priorities
- 5.4 Comparing the escape timescale to impact and ascent timescales

6. A Minimal Impact Clock Model of Civilizational Dynamics

- 6.1 State space: pre-technological, proto-technological, radio-loud, and collapsed
- 6.2 Impacts as stochastic transitions on this state space
- 6.3 Duty cycles: fraction of time a world spends in each civilizational state
- 6.4 Analytic and numerical sketches of regimes: quiet, intermittently loud, and robust

7. The Stone-Age Galaxy: Interpreting a Low Duty Cycle

- 7.1 What a low radio-loud fraction looks like from a SETI perspective
- 7.2 Worlds full of intelligent survivors with no detectable technosphere
- 7.3 Myth, archaeology, and “previous cycles” of technology on the same planet
- 7.4 Distinguishing “we are alone” from “we are listening at the wrong times”

8. Complementarity with Other Great Filters

- 8.1 Self-inflicted filters: war, climate, pandemics, and AI misalignment
- 8.2 Astrophysical filters: flares, supernovae, GRBs, and stellar evolution
- 8.3 Cultural filters: voluntary stagnation, inward turns, and anti-expansion ethics
- 8.4 Impact clocks as amplifiers: how external shocks interact with internal fragility

9. Observational Consequences and Possible Tests

- 9.1 Signatures of repeated rise-and-fall on exoplanets and in spectra
- 9.2 Technosignature archaeology: debris, altered atmospheres, and orphan satellites
- 9.3 Constraints from Earth’s own impact and extinction record
- 9.4 Conceptual experiments: simulated planets under impact clock dynamics

10. Planetary Defense as a Great Filter Crossing

- 10.1 Deflecting city-killers: deliberately altering the impact clock
- 10.2 Extending the radio-loud window: from centuries to millennia and beyond
- 10.3 Crossing into the robust regime: when impacts cease to be existential for tech
- 10.4 A civilizational milestone: a species that tames its own reset clock

11. Ethical and Philosophical Implications

- 11.1 Civilizations as transient patterns between random external shocks
- 11.2 Intergenerational responsibility under an active impact sky
- 11.3 What we would owe to future intelligences on Earth if we fail
- 11.4 Meaning, humility, and purpose in a universe of interrupted stories

12. Synthesis: Is the Impact Clock Enough to Explain the Silence?

- 12.1 Summarizing the impact clock hypothesis in Fermi terms
- 12.2 Conditions under which impact resets alone could yield a quiet galaxy
- 12.3 Why “probably a major factor” is more plausible than “sole explanation”
- 12.4 Open questions for astrobiology, risk science, and long-term strategy

13. References

- 13.1 Impact physics, crater statistics, and extinction literature
- 13.2 Fermi Paradox, Great Filter, and SETI frameworks
- 13.3 Models of collapse, resilience, and technological vulnerability
- 13.4 Ethical, philosophical, and policy treatments of planetary defense

1. Introduction: From Impact Craters to a Stone-Age Galaxy

Every inhabited world carries scars. Some are chemical and subtle, recorded in isotopes and fossil shells. Others are brutally obvious: craters hundreds of kilometers wide, global ash layers, sudden breaks in the fossil record. On Earth, one such scar – the buried Chicxulub crater – marks a moment when an asteroid delivered energy far beyond anything a technological civilization has ever wielded, erasing the non-avian dinosaurs and reshaping the trajectory of life. Smaller impacts, volcanic super-eruptions, and other natural catastrophes also punctuate the geological archive.

Technological civilizations, if they arise, emerge against this backdrop of intermittent violence. They are not free-floating abstractions; they are patterns precariously maintained in matter, energy, and social organization on the surface of a restless planet. The Fermi Paradox asks why, given the age and scale of the galaxy, we see no clear evidence of other such patterns beyond Earth. Standard answers often focus on one-off catastrophes, self-inflicted ruin, or cultural choices not to expand. This paper explores a different possibility: that many civilizations are repeatedly interrupted by an external metronome – an “impact clock” – that periodically knocks them down to pre-industrial or even stone-age conditions without extinguishing the species itself.

In that picture, the galaxy can be full of intelligent survivors and buried ruins, yet appear quiet to our telescopes and radio receivers. The question is not only “do they exist?” but “how often are they in a state where we can notice them?” To address this, we frame planetary history in terms of three interacting clocks: the impact clock, which governs natural resets; the technological ascent clock, which governs how rapidly civilizations arise and rebuild; and the escape clock, which measures how long it takes to acquire enough off-world robustness that impacts cease to be existential for technology.

1.1 The Fermi question, narrowed to peer-level technological civilizations

The canonical Fermi question – “Where is everybody?” – hides multiple sub-questions. Are there other biospheres at all? Are there other intelligent species? Are there other technological civilizations? And, more specifically, are there any civilizations roughly comparable to ours, currently capable of electromagnetic communication, spaceflight, or engineering projects on planetary scales?

This paper narrows focus to that last tier: peer-level technological civilizations. We are not trying to explain why we see no microbes on exoplanets, nor why we have no obvious evidence of Kardashev type II or III megastructures. Instead, we ask a more modest but concrete question: why, at this particular moment, do we not detect any other civilizations with capabilities broadly similar to ours?

Peer-level here is deliberately fuzzy. It encompasses societies that can build radio telescopes, launch probes, deploy satellites, and perhaps maintain a small presence beyond their home world, but that are still tightly coupled to a single planet's surface infrastructure. Such civilizations are powerful enough to be detectable over interstellar distances for a time, yet fragile enough that external shocks and internal failures can erase their technosphere. If many worlds achieve this level intermittently but only remain in it for short, scattered intervals, then the probability that any two such civilizations overlap in time becomes small, even if the galaxy is generically fertile.

By narrowing the Fermi question in this way, we shift from "Why is there no life or intelligence?" to "Why are there no peers on the air right now?" That narrower question is precisely where an impact-driven, cyclical-reset picture can be most informative.

1.2 Why recurrent natural resets matter more than one-off catastrophes

Most dramatic explanations of cosmic silence rely on singular events: a rare gamma-ray burst sterilizing vast regions, a unique phase transition in physics, or a one-time great filter that nearly all lineages fail to pass. While such possibilities cannot be ruled out, planetary history as we know it is not shaped by a single catastrophe but by a sequence of shocks of varying magnitude. On Earth, there have been multiple mass extinctions, many large impacts, countless regional disasters. Life did not end with any of them; instead, evolutionary and ecological trajectories were deflected.

For civilizations, the key distinction is between extinction and reset. An extinction event removes a lineage entirely; there is no one left to rebuild. A reset event destroys infrastructure, compresses populations, and erases complexity, while leaving survivors capable of cultural continuity and, eventually, technological rediscovery. From the standpoint of detectability, repeated resets can be more important than a single final catastrophe. They carve planetary history into intermittent windows during which advanced technology exists, with long dark intervals in between.

If resets are frequent relative to the timescale on which complex technology arises and spreads, then the average duration of a civilization's detectable phase is short. Even if the same species rebuilds multiple times, each radio-loud episode may last only centuries or millennia before another impact, super-eruption, or combined disaster pushes it back into a low-tech state. A radio telescope on another world looking toward Earth over millions of years would see, at best, brief flashes of artificial activity separated by vast stretches of silence.

In this sense, recurrent natural resets act as a kind of external censorship. They do not forbid intelligence, but they reduce the duty cycle of advanced technology. When combined with other internal hazards – war, pandemics, climate disruption – they create a layered vulnerability:

civilizations are not only fragile once, at the moment of their first ascent, but repeatedly, every time they climb back toward high complexity.

1.3 Three clocks on an inhabited planet: impact, ascent, and escape

To make this intuition more precise, it helps to think in terms of three conceptual clocks ticking on any inhabited world.

The first is the impact clock. It measures the stochastic arrival of large external insults: asteroid and comet impacts, perhaps also certain extreme volcanic or astrophysical events. Its ticks are not regular like a metronome, but they have characteristic frequencies for different energy scales. Small impacts happen often, city-killers less often, Chicxulub-class events rarer still. Yet over the lifetime of a planet, many such ticks accumulate.

The second is the technological ascent clock. It measures how long it takes for a species, once it has the biological and cultural preconditions, to crawl from fire and tools to global industrial infrastructure, digital communication, and spaceflight. This clock does not tick on its own; it advances only under favorable conditions, and can pause or rewind under ecological stress or social collapse. Different worlds may have very different ascent times depending on climate stability, resource distribution, social structures, and sheer contingency.

The third is the escape clock. It starts when a civilization becomes capable of sustained off-world activity and measures the time required to achieve genuine robustness against planet-bound catastrophes. That robustness might come from self-sufficient colonies on other worlds, widely distributed orbital industry, or swarms of autonomous probes carrying its knowledge far beyond the reach of a single planet's disasters. When the escape clock "rings," the civilization has diversified enough that no single impact on any one planet can fully erase its technological presence.

The interaction of these three clocks shapes a world's history. If the impact clock ticks faster than the ascent clock can complete, civilizations may never reach radio-loud phases at all. If the ascent clock regularly gets ahead of the impact clock but the escape clock is slow, civilizations will emerge, briefly flourish, and be knocked back repeatedly, spending only a tiny fraction of their planetary history in technologically advanced states. If the escape clock tends to beat the next large impact, a world may seed a multi-planetary network before the next big reset, turning impacts into local disasters rather than global civilizational resets.

1.4 Overview of the impact clock hypothesis and the structure of the argument

The impact clock hypothesis claims that, on many Earth-like planets, the statistical interplay of these three clocks strongly suppresses the fraction of time during which peer-level technological civilizations exist and are detectable. In this view, the galaxy may not be empty of intelligence; it

may be full of worlds where intelligent species cycle between low-tech and high-tech phases, with natural resets frequently truncating their attempts to become robustly multi-planetary. From our vantage point, the odds of catching such a world during one of its brief high-tech intervals are small, especially if our own interval is only just beginning.

The argument of this paper unfolds in several stages. First, we examine what kinds of impact energies are sufficient to erase a technological civilization without exterminating its host species, and how often such events are expected on Earth-like planets. Second, we sketch plausible timescales for technological ascent and for the development of off-world robustness, emphasizing the uncertainty and variability but also the constraints imposed by physics and engineering. Third, we build a minimal dynamical model in which impacts randomly reset civilizations that have not yet escaped, and we analyze the resulting duty cycle of radio-loud phases.

With that framework in place, we explore what a “stone-age galaxy” would look like from a SETI perspective: a cosmos where many worlds host intelligent life, but most of the time that life is either pre-technological or recovering from collapse, with only intermittent, planet-specific episodes of detectability. We then situate the impact clock hypothesis among other proposed Great Filters, arguing that it is unlikely to be the sole explanation for cosmic silence but may be a major amplifier of other vulnerabilities. Finally, we consider the implications for planetary defense and long-term strategy on Earth: if we are indeed in an early radio-loud window under an active impact sky, then the choice to alter our impact clock – by detecting and deflecting hazardous objects – could be one of the decisive acts that determines whether our story becomes another interrupted fragment or a seed for a more resilient presence in the galaxy.

2. Energy and Fragility: What It Takes to Erase a Civilization

Technological civilizations are built on a thin, intricate layer of infrastructure draped over a planet: power grids, fiber networks, transport systems, industrial complexes, data centers, farms, and cities. From the ground, these structures feel massive and permanent. From the vantage point of planetary physics, they are delicate surface patterns sitting atop a far larger reservoir of energy and momentum. To understand how easily they can be erased, we need a way of comparing wildly different phenomena: nuclear tests, earthquakes, asteroid impacts, and the daily flow of solar energy.

This section adopts megatons of TNT equivalent as a practical common currency. It then uses the stark contrast between a 20 megaton event and a roughly 10^8 megaton Chicxulub-class impact to anchor intuition. Against that backdrop, we explore the thresholds at which damage shifts from regional catastrophe to global infrastructural collapse, and finally to deep biospheric

restructuring. The key point is that there exists a substantial regime of “reset energies” large enough to destroy cities and complex infrastructure while leaving the underlying biosphere, and the intelligent species it supports, largely intact. That regime is where the impact clock becomes an effective civilization eraser without being a species exterminator.

2.1 Megatons as a common currency for bombs, earthquakes, and impacts

Energy can be measured in many units, but megatons of TNT have become the intuitive benchmark for large explosions. One megaton is defined as the energy released by detonation of one million tons of TNT. In physics terms, that corresponds to about 4.184×10^{15} joules. The advantage of megatons is that they bridge three domains at once.

First, they are rooted in human engineering. Thermonuclear devices reach yields of tens of megatons; historical testing has given us a visceral sense of what such events do to cities, landscapes, and the atmosphere. When we say an asteroid impact is “like” a large bomb, we mean it releases a similar amount of energy, even though the physical process is very different.

Second, megatons provide a convenient way to talk about natural catastrophes. Large earthquakes, for example, release energies comparable to tens or hundreds of megatons, albeit spread over minutes and along fault planes rather than concentrated in a single point. Volcanic eruptions and super-eruptions can match or exceed these scales. Using megatons for all of them allows us to compare how much “work” each event can do on the planet’s crust, oceans, and atmosphere.

Third, megatons offer a straightforward link to kinetic impacts. The energy of an asteroid or comet is one half times its mass times the square of its velocity. When we plug in typical impact speeds of tens of kilometers per second and plausible sizes from tens of meters to tens of kilometers, the resulting energies naturally fall into kiloton and megaton scales. A 50 meter rock might deliver a few megatons; a 10 kilometer body delivers on the order of 10^8 megatons. With one unit, we can compare an H-bomb, a major quake, and a Chicxulub-like impact.

This unified energy language does not erase the differences between phenomena, but it lets us say meaningful things like: “this impact released more energy than all nuclear weapons ever built” or “this quake rivaled a medium-sized asteroid strike.” For thinking about civilizational fragility, such comparisons are essential.

2.2 The five-million-to-one contrast: 20 megatons versus 10^8 megatons

Within this megaton framework, the contrast between a 20 megaton event and a 10^8 megaton event is brutally simple. The latter is five million times more energetic than the former. If we take 20 megatons as a rough proxy for a very large H-bomb or a substantial city-killer asteroid

airburst, and 10^8 megatons as a placeholder for a Chicxulub-class impact, the ratio between “erase a region” and “restructure the biosphere” is six orders of magnitude.

Part of the point of this paper is that we should not let that ratio blur into “Chicxulub is bigger.” A factor of two or ten can sometimes be handled with intuition; a factor of five million cannot. To get any grip on it, we have to lean on scaling rules. Crater diameter grows sublinearly with energy, roughly like energy to the one-third power in some regimes. That means a five-million-fold increase in energy might translate into a one- to two-hundred-fold increase in crater size. Devastation radii, blast overpressures, and thermal footprints behave in similar power-law ways: they grow dramatically, but not in proportion to the raw energy.

In consequence, a 20 megaton impact or airburst is catastrophic on human scales but limited geographically. It can erase a metropolis, flatten a region, trigger tsunamis, and throw enough dust and aerosols into the atmosphere to produce short-term climate anomalies. A 10^8 megaton impact, by contrast, can ignite global firestorms, loft sunlight-blocking material to the stratosphere for years, acidify oceans, and drive a mass extinction visible in the fossil record.

For the impact clock hypothesis, both ends of this contrast matter. Chicxulub-scale events define the deep-time tempo for resetting entire biospheres. Sub-Chicxulub impacts in the tens to thousands of megatons define a separate regime where civilizations can be toppled without necessarily altering the basic habitability of the world. The five-million-to-one contrast reminds us that these two filters, biosphere-level and civilization-level, live on different rungs of the same exponential ladder.

2.3 Thresholds: from regional disaster to global infrastructural collapse

The fate of a civilization in the face of an impact is not determined by total energy alone. It is governed by thresholds: how much infrastructure lies within the blast radius, how intertwined global systems are, how dependent critical functions are on vulnerable hubs, and how quickly reserves and redundancies can compensate for local losses. In this sense, there is a spectrum of impact energies and geometries mapping onto qualitatively different outcomes.

At the lower end, sub-megaton to single-digit megaton events can cause local or regional disasters. A Tunguska-like airburst over an unpopulated area flattens forests but leaves civilization intact, though shaken. Over a city, a similar event would be a catastrophe, but the global system would likely absorb it: other regions could supply food, energy, and materials; knowledge and digital records stored elsewhere would survive; and the event would enter history as a tragedy, not as the end of the technological era.

As we move up the scale into tens or hundreds of megatons, impacts or clusters of impacts begin to threaten global infrastructure. A 20 megaton object that explodes over or near a coastal megacity, or strikes the ocean close to major trade routes, can destroy dense

populations, critical ports, and financial centers in one stroke. If it triggers tsunamis reaching multiple continents, destroys key undersea cables, knocks out a substantial fraction of satellite constellations through debris or electromagnetic effects, and coincides with existing stresses such as pandemics or political instability, the event can tip global systems into cascading failure.

Above some threshold, which depends on geography and technological architecture, the world's infrastructure ceases to be repairable within a single human generation. Power grids that rely on specialized components no longer manufactured, global supply chains broken at multiple points, and agricultural systems tuned to just-in-time logistics can all fail together. Once the critical mass of continuity is lost, recovery paths become long and uncertain. In that regime, an impact does not simply "kill a lot of people"; it erases the conditions that made high technology possible.

Crucially, this threshold for global infrastructural collapse can be reached at energies far below Chicxulub. The planet's crust, oceans, and atmosphere can absorb a 100 or 1,000 megaton blow with relatively modest long-term physical changes, but fragile, highly centralized technological systems may not. That mismatch between planetary robustness and civilizational fragility is where reset events live.

2.4 Destroying cities without destroying species: the reset regime

The reset regime consists of impacts and related catastrophes that destroy the visible surface of civilization while leaving the underlying biology and cognition largely intact. In this regime, the species survives, often in great numbers, but its technological pattern is shattered. Cities are obliterated or abandoned, industrial capacity is lost, and complex social networks fragment into smaller, more local structures.

From the standpoint of detectability, this is the most important range of energies. A world in the reset regime may be full of intelligent beings who remember or mythologize previous high-tech eras, yet it will present no strong technosignature to distant observers. Its atmosphere returns to a roughly natural composition; its night side shows no widespread artificial lighting; its radio spectrum is quiet. Archaeological signatures exist on the ground, perhaps even in orbit or on the Moon, but they are not easily visible across interstellar distances.

Several properties make the reset regime likely on Earth-like worlds. First, the human body – and by extension, the bodies of many intelligent species – is robust enough to survive intense regional trauma, especially if buffered by refugia far from impact zones. Second, knowledge is vulnerable not only to physical destruction but to the loss of institutions and media required to transmit it. A few generations without schooling, printing, or digital storage can erase most of the practical content of advanced science and engineering, even if myths and stories about a fallen high-tech age persist.

Third, ecosystems are resilient on longer timescales. Even a severe blow to infrastructure and a sharp human population decline need not correspond to a mass extinction in the biological sense. Forests regrow over abandoned cities; wild animals recolonize once-industrial zones. From a purely ecological perspective, the reset regime can look like a minor perturbation or even a release from anthropogenic pressure. It is only at the level of cultural complexity that the event is catastrophic.

The impact clock hypothesis builds on this reset regime. It suggests that, given plausible impact frequencies and the fragility of early global civilizations, many worlds will experience repeated episodes in which intelligent species achieve industrial and digital complexity, only to have those patterns wiped away by impacts that are modest by planetary standards. Each time, survivors may rebuild or may not, depending on subsequent conditions. For external observers, the planetary technosignature blinks on and off over geological timescales. When we look out and see mostly darkness, it may not mean there are no minds, but that most of them currently live in worlds that have been reset to something resembling our own deep past: rich in memory, perhaps, but poor in detectable machines.

3. Impact Climatology: Recurrence Rates on Earth-like Worlds

To understand how often civilizations are likely to be reset, we need a kind of “climate” for impacts: not weather in the usual sense, but long-term statistical patterns in the arrival of rocks. Impact climatology treats asteroid and comet strikes the way meteorologists treat storms, emphasizing frequencies, intensities, and rare extremes rather than individual events. On Earth, this climatology is encoded in the crater record, in sediment layers bearing shocked minerals and extraterrestrial elements, and in the growing census of near-Earth objects.

The emerging picture is simple in spirit and brutal in implication. Small impactors are common, large ones are rare, and very large ones are extremely rare. Yet over hundreds of millions or billions of years, even extremely rare events become almost inevitable. Against this statistical backdrop, any given civilization occupies a short, vulnerable interval. Whether it survives to become robustly multi-planetary depends not just on its internal choices, but on where it happens to fall relative to the next few ticks of the impact clock.

3.1 The size–frequency distribution of impactors

The first pillar of impact climatology is the size–frequency distribution of impactors. Observations of asteroids and comets, together with crater statistics on Earth, the Moon, and other bodies, suggest that the number of objects larger than a given size follows a power law. Roughly speaking, there are many small objects, fewer medium-sized ones, and very few large ones, with each step up in size accompanied by a steep drop in number.

In practical terms, this means that meter-scale stones capable of producing bright fireballs and small airbursts hit the atmosphere frequently, perhaps every year or less. Tens-of-meters objects, large enough to produce a Tunguska-class event if they fragment low in the atmosphere, are rarer, with recurrence times often estimated in centuries. Hundred-meter to kilometer-scale objects, capable of producing city-killer or regional-scale craters, are rarer still, with recurrence times stretching into tens or hundreds of thousands of years. Chicxulub-class bodies on the order of ten kilometers across sit at the extreme tail, with impact intervals measured in tens or hundreds of millions of years.

The power-law character of the distribution is crucial. It implies that no single size range dominates all risk; instead, different size ranges dominate different kinds of risk. Small bodies contribute constantly to the background of minor events. Medium bodies dominate the threat to cities and regional infrastructure. Very large bodies dominate the threat to entire ecosystems and the long-term trajectory of life. Civilizations live under the combined influence of all these size classes, each associated with its own characteristic energy and potential to reset or extinguish.

3.2 Recurrence times for Tunguska-class, city-killer, and sub-Chicxulub events

Within this framework, we can define three broad energy bands relevant for the impact clock hypothesis. The first is the Tunguska-class band: events releasing on the order of one to a few tens of megatons. These are typically associated with tens-of-meters objects that disintegrate in the atmosphere, generating powerful airbursts that can flatten forests or devastate cities but may or may not leave craters. Estimates for their recurrence times on Earth fall in the range of centuries to millennia.

The second band is the city-killer band, centered around events of order tens of megatons, such as our canonical 20 megaton case. Impactors in this class may be slightly larger and more robust, capable of penetrating deeper into the atmosphere or striking the surface. A 20 megaton airburst or impact over land or coastal waters near major population centers would be a defining catastrophe for human civilization. Order-of-magnitude estimates suggest that such events may occur on timescales of thousands to perhaps tens of thousands of years on Earth-like worlds, though uncertainties remain substantial.

The third band is the sub-Chicxulub but super-city-killer regime, spanning roughly hundreds to perhaps a million megatons. Events in this range may be caused by kilometer-scale objects and can produce large regional or even hemispheric disturbances. They can generate multi-hundred-kilometer craters, inject enormous quantities of dust and aerosols into the atmosphere, and significantly perturb climate for years. Recurrence times for these events lengthen into the

hundreds of thousands or millions of years. Chicxulub itself, at roughly 10^8 megatons, lies near the top of this band, with estimated recurrence intervals at least tens of millions of years.

These numbers are rough and planet-specific. They depend on the particular architecture of a planetary system, the population of impactor reservoirs, and the efficiency of scattering processes that deliver bodies to the inner regions. However, the qualitative structure is robust: modest impactors that can destroy cities are much more frequent than Chicxulub-class biosphere resetters. For the fate of civilizations, the first two bands matter most, because they operate on timescales comparable to or shorter than plausible spans of technological history.

3.3 Chicxulub-scale events as biosphere filters, not just civilization filters

Chicxulub-scale events occupy a distinct category in impact climatology. Their hallmark is not simply high energy, but the ability to reconfigure entire ecosystems and alter evolutionary trajectories. On Earth, the impact that marked the boundary between the Cretaceous and Paleogene periods coincided with a mass extinction that eliminated many large vertebrate lineages and opened ecological niches subsequently occupied by mammals and birds.

From the standpoint of the impact clock, such events function less as civilization filters and more as biosphere filters. If a technological civilization already exists at the time of a Chicxulub-class impact, its survival prospects are dire. The combination of global firestorms, prolonged darkness, acid rain, and disrupted food webs is likely to erase not only its infrastructure but also a large fraction of its population, potentially beyond recovery. The species itself may go extinct.

At the same time, Chicxulub-scale events also shape the long-term probability that technological civilizations will arise at all. By periodically wiping out dominant clades and reshuffling ecological possibilities, they influence which lineages get the opportunity to evolve complex cognition, manual dexterity, and social structures conducive to technology. In that sense, they occupy a deeper level of the Great Filter hierarchy. A world that experiences too many Chicxulub-class blows in rapid succession may never sustain stable, long-lived ecosystems capable of evolving intelligence. A world that experiences too few may remain dominated by long-lived but non-technological lineages.

For the purposes of this paper, Chicxulub-scale events set the outer frame of the impact climatology. They are rare enough that multiple technological cycles could, in principle, occur between them on a given world. But when they do occur, they can reset not only civilizations but the entire roster of potential civilization-bearing species. The more frequent, lower-energy impacts then act within each biospheric era as civilization-specific reset agents, repeatedly knocking societies back before they can escape their planet's surface.

3.4 Variability across planetary systems: thick tails and unlucky worlds

So far, the discussion has used Earth as a template. In reality, impact climatology will vary from system to system. Some planets may live in relatively quiet neighborhoods, with sparse asteroid belts and efficient gravitational shields provided by giant planets that sweep up or deflect many potential impactors. Others may orbit stars with rich debris disks, multiple resonances that funnel objects inward, or nearby comet reservoirs that periodically destabilize.

This variability introduces thick tails into the distribution of impact histories. A substantial fraction of Earth-like planets might enjoy calmer skies than ours, with longer intervals between city-killer and sub-Chicxulub events. On such worlds, the ascent and escape clocks would have more time to run, increasing the chance that civilizations reach multi-planetary robustness before the next major blow. Conversely, some worlds may be unlucky, with unusually high impact fluxes that prevent complex life from stabilizing or repeatedly devastate emerging civilizations before they can become resilient.

Stellar and galactic environments also matter. Planets in dense stellar clusters may be exposed to more frequent perturbations of their comet reservoirs. Planets closer to the galactic center may experience higher background levels of radiation and more gravitational nudges that disturb small-body populations. Over billions of years, these differences in environment can lead to markedly different impact clocks, even among planets that are superficially similar in mass and composition.

For the Fermi question, this variability means that there is no single “typical” impact history. Instead, there is a spectrum ranging from very safe to very hazardous. Civilizations arising on quiet worlds may find the impact clock a minor nuisance, easily managed once basic planetary defense capabilities are developed. Civilizations on unlucky worlds may never get that far, or may do so only rarely. From our vantage point, embedded in one particular system with one particular history, we see only a single realization. The impact clock hypothesis invites us to imagine a galaxy where many such clocks tick at once, some slow, some fast, shaping when and whether peer-level civilizations are available to be heard.

4. The Technological Ascent Clock

If the impact clock is the external metronome, the technological ascent clock is the internal tempo at which a species learns to rearrange matter, energy, and information. It measures how long it takes to go from a clever animal with tools and speech to a civilization capable of building radios, rockets, and global networks. The impact clock does not care about this progress; it ticks on regardless. Whether a civilization ever becomes visible to distant observers depends on

whether its ascent clock can finish key stages before some combination of external shocks and internal failures resets the board.

This section sketches a minimal technological pathway from fire to radio, outlines plausible timescales for industrialization and global networking, and considers how environmental and cultural contingencies might accelerate or slow ascent. It closes by asking how often intelligent species might get “close” to our level without fully converging on it, leaving behind rich local histories but no strong technosignatures.

4.1 From fire to radio: sketching a minimal technological pathway

Any real technological history will be messy, with sidetracks, dead ends, and unique cultural inventions. For impact clock purposes, however, we only need a coarse-grained, minimal pathway that captures the major functional transitions. One such sketch might look like this.

At the base is mastery of fire and tools. Controlled use of fire allows cooking, which changes diets and time budgets, and provides warmth and protection. Persistent tool use, combined with cumulative culture, yields increasingly sophisticated hunting, building, and crafting techniques. Language and social learning make it possible for innovations to spread and accumulate rather than being rediscovered from scratch each generation.

The next layer is agriculture and settled life. Domestication of plants and animals increases energy availability per unit land and supports higher population densities. Sedentary communities create pressures and opportunities for new forms of social organization, from villages to chiefdoms to early states. Surplus production supports specialization: some people no longer farm but instead become craftspeople, scribes, or priests.

Metallurgy and writing mark another transition. Working copper, bronze, and iron unlocks new tools and weapons. Writing systems enable long-distance administration, contracts, history, and technical records. With these, large polities can coordinate projects that no small band could manage: irrigation networks, road systems, monumental architecture, and eventually early mechanical devices.

Beyond this lies systematic science and the exploitation of fossil fuels. Empirical inquiry coalesces into methods capable of isolating regularities in nature. Coal, oil, and gas are harnessed not just as heat sources but as drivers of engines, factories, and transport networks. Mechanical power is decoupled from muscle, wind, and water.

Finally come electricity, electronics, and radio. Understanding and harnessing electromagnetism allows for telegraphy, lighting, motors, and long-distance communication. Radio in particular is a tipping point for detectability: it permits deliberate broadcasting and creates a background of leakage that can, in principle, be seen across interstellar distances. Once a civilization begins

beaming high-power signals into the sky or fills its near space with active transmitters, its ascent clock has reached a state relevant to the Fermi question.

This is a minimal path. There are many possible variations. Some species might develop sophisticated mathematics and astronomy before heavy industry, others might leapfrog certain steps with different energy sources or information technologies. But for our purposes, the key is that there is a sequence of enabling transitions, each depending on previous ones, and each vulnerable to interruption.

4.2 Plausible timescales for industrialization and global networking

On Earth, the full span from early agriculture to radio took on the order of ten thousand years, depending on where one draws the boundaries. The interval from the first recognizably industrial societies to the first radio transmissions was much shorter, perhaps a century or two. Global networking, in the sense of near-instantaneous communication around the planet and integrated economic systems, emerged within another century. These numbers are small compared to the age of the biosphere, but large compared to individual human lifetimes and political cycles.

For other worlds, there is no reason to expect identical timing. The ascent clock might run faster or slower. A species with a longer natural lifespan might compress more learning into each generation, shortening the number of generations needed to discover key principles. A planet with unusually abundant and accessible energy sources and mineral deposits might accelerate industrialization once a certain conceptual threshold is crossed. Conversely, a world with sparse resources or harsh climate may slow ascent, forcing long periods of stable, low-tech adaptation.

Nevertheless, there are constraints. The discovery of controlled fire, agriculture, metallurgy, and empirical science each require environmental and social conditions that are not trivial to satisfy. From a planetary standpoint, it is reasonable to think in terms of broad ranges: perhaps thousands to tens of thousands of years from the first complex societies to industrialization, and hundreds to thousands of years from early industry to a fully global, radio-loud technosphere.

These ranges matter because they must be compared to the recurrence times of serious impacts and other external shocks. If the interval between city-killer-scale events is shorter than the time needed to go from pre-industrial society to a robust, globally networked technological civilization, then the ascent clock will repeatedly be interrupted. If the interval is longer, the ascent clock has a chance to “finish its lap” and pass the baton to the escape clock.

4.3 Cultural and environmental contingencies on ascent speed

The ascent clock is not purely a function of biology and physics; it is also shaped by culture and environment. Two worlds with similar impact climatologies and cognitive capacities could have

very different ascent times depending on how their societies organize knowledge, power, and innovation.

Geography plays a role. Continents with varied climates and many semi-isolated regions can support parallel experiments in agriculture, governance, and technology. Innovations arising in one region can later diffuse to others. Conversely, a single supercontinent with uniform climate might see more homogeneous cultural development, possibly reducing the diversity of experiments. The distribution of domesticated species matters as well. Ready access to animals and plants that can be domesticated efficiently can accelerate the transition to agriculture and surplus production.

Resource endowment is another factor. The presence of near-surface fossil fuels, accessible ores, and usable building materials can shorten the path to industry. A world whose accessible iron is mostly locked in difficult-to-process forms, or whose hydrocarbon reserves are minimal, might develop very differently, perhaps relying on direct solar, geothermal, or other unconventional energy sources. In such a world, industrialization might be delayed or follow a route unfamiliar to us.

Cultural attitudes toward inquiry and change also modulate ascent. Societies that encourage exploration, tolerate dissent, and reward technical problem-solving may accelerate scientific discovery. Those that rigidly constrain thought or enforce strict traditional patterns may slow or redirect it. Religious, philosophical, or ideological frameworks can either integrate technological change into a broader worldview or resist it as a threat.

In addition, repeated smaller-scale disasters, wars, and collapses can stretch out the ascent clock. Civilizations may rise and fall several times, each time recovering some fraction of previous knowledge but not all. The existence of ruins and legends of past wonders can either motivate renewed ascent or be interpreted as cautionary tales that discourage certain paths. The ascent clock is therefore not a smooth monotonic progression; it can jump forward, stall, or even reverse.

4.4 How often does a species “get close” without fully converging on our trajectory?

From the perspective of the impact clock hypothesis, an important question is not just whether civilizations reach our current level, but how often they get near without fully converging on it. A species might develop metallurgy, writing, city-states, and even modest mechanical devices without ever discovering radio or building spaceflight. It might construct remarkable works of art, philosophy, and local engineering, yet remain undetectable from afar.

There are several ways to get close without arriving. One is to develop sophisticated pre-industrial societies that plateau. These societies might achieve stable agricultural systems, long-distance trade, and rich intellectual traditions but never transition to fossil-fuel-driven industry.

Reasons could include limited accessible resources, cultural or religious prohibitions, or simply a lack of conceptual breakthroughs in key areas like thermodynamics or electromagnetism.

Another is to experience cycles of partial industrialization followed by collapse. A civilization might discover steam power, basic electricity, or even primitive radio, but then be undone by war, pandemics, or moderate natural disasters before achieving global integration. If records and infrastructure are sufficiently destroyed, subsequent societies may inherit only fragments of this knowledge, leading to a pattern of repeated near-misses.

A third possibility is divergence into alternative technological paths that do not produce strong remote signals. A species might become highly adept at biology, materials science, or low-energy local computing without ever building large, noisy radio systems. It might prefer optical communication, wired networks, or other channels that are much harder for distant observers to detect. In such cases, the civilization's ascent clock reaches a form of advanced technology, but the particular branch chosen does not light up the sky.

The interaction with the impact clock is subtle. Each near-miss still takes time: centuries or millennia in which a civilization is vulnerable to being reset. If impacts or other external shocks occur frequently enough, they can truncate these near-miss trajectories repeatedly. Worlds may therefore accumulate deep cultural layers of "almost but not quite," with myths of flying machines, great fires, or vanished towers, but no continuous thread leading to spaceflight and robust, multi-planetary existence.

From a distant vantage point, these histories are largely invisible. What matters is whether, at the moment we are listening, a given world has a civilization that both possesses and uses technologies that generate detectable technosignatures. The technological ascent clock captures how quickly and how often a species reaches states in which this is possible. The more often ascent is interrupted, the more likely it is that at any randomly chosen time, even an intelligent world will present itself as quiet, with its inhabitants, perhaps, staring at their own cratered sky and telling stories about the last age when the gods walked among them and machines spoke across the air.

5. The Escape Clock: Time to Multi-Planetary Robustness

If the technological ascent clock measures how fast a species climbs to radio and rockets, the escape clock measures something harder: how long it takes before no single planetary disaster can erase its technosphere. Until that point, a civilization is fundamentally local. Its industry, data, and population are concentrated in a thin shell on one world. An impact, super-eruption, or combination of shocks can still push it back into a dark age or even to pre-industrial conditions. Once the escape clock "rings," the civilization has crossed a qualitative threshold. It

has become multi-planetary or at least multi-site in a way that decouples its survival from any one impact on any one surface.

This section sharpens what counts as “escape,” sketches key engineering constraints, explores social and political hurdles, and then compares the escape timescale to the impact and ascent timescales. The central question is simple: can a civilization typically build robust off-world footholds before the next tick of the impact clock or not?

5.1 Defining “escape”: off-world industry, self-sustaining colonies, or probes

Escape is not a binary switch but a spectrum. At one end, there is purely symbolic spaceflight: a few brief missions, maybe a small research outpost, heavily dependent on continuous support from the home planet. At the other end, there is a fully multi-planetary network of habitats, industries, and possibly autonomous probes spread across interplanetary or even interstellar distances. Somewhere along this continuum lies a practical threshold beyond which impact-driven resets on the home world cease to threaten the persistence of advanced technology as such.

One functional definition of escape is the existence of off-world industry capable of reconstructing high technology even if the home planet’s surface infrastructure is destroyed. This could mean asteroid mines and orbital factories that do not rely on supplies from below, or large habitats that can build their own replacement parts, launch vehicles, and energy systems. In this scenario, a civilization’s knowledge and productive capacity are no longer hostage to a single biosphere.

A stricter definition is the establishment of self-sustaining colonies: populations living off-world with enough genetic, cultural, and material diversity to persist for many generations without resupply. These colonies might be on nearby planets or moons, in free-floating habitats, or in engineered environments around other stars. The key property is autonomy. They can survive and adapt even if the home planet is rendered uninhabitable or technologically primitive.

A looser but still meaningful notion of escape involves probes and data. A civilization that seeds other systems with autonomous probes, archives, or engineered lifeforms ensures that its technological lineage cannot be completely erased by a single impact. Even if the home species dies out, artifacts continue to operate, observe, or evolve elsewhere. This kind of “probe escape” does not protect the originating population, but it does break the link between a single planet’s impact history and the long-term presence of technosignatures in the galaxy.

In practice, escape may be achieved in layers. A civilization might first develop limited off-world industry, then more robust orbital infrastructure, then one or more self-sustaining colonies, and eventually a distributed network. The escape clock measures the time required to cross

whatever threshold we choose: enough off-world presence that home-world resets are no longer synonymous with technological extinction.

5.2 Engineering constraints: launch windows, energy budgets, and materials

Engineering realities impose hard lower bounds on the escape timescale. Reaching orbit requires overcoming gravity and atmospheric drag; this is not optional. The rocket equation dictates that chemical rockets must carry large masses of propellant relative to payload, especially for launch from dense atmospheres. Building launch vehicles, propellants, and guidance systems at scale requires substantial industrial capacity and a deep materials and energy base.

Energy budgets matter. Sustained off-world activity demands large power sources, whether chemical, solar, nuclear, or something more exotic. Mining and processing material in space, constructing habitats, and maintaining life-support systems are all energy-intensive. Early spaceflight can piggyback on the home world's industrial plant, but as long as space infrastructure depends on a mature ground-based economy, it shares that economy's vulnerability to impacts and other shocks. Transitioning to space-based power and industry is a non-trivial engineering and logistical project.

Launch windows and orbital mechanics also influence timing. Efficient transfers between planets or asteroids occur only during certain alignments. Building up a significant off-world presence means planning around these cycles, which can stretch into years. This does not dramatically lengthen the overall escape clock compared to civilizational timescales, but it introduces lags and bottlenecks. A civilization cannot scatter to the stars overnight, no matter how advanced its engines, because infrastructure must be built stepwise in environments that are physically hostile.

Materials constraints add another layer. Life-support systems require redundancy and reliability that go beyond most terrestrial engineering. Radiation shielding, closed-loop ecosystems, and robust recycling technologies are necessary for long-lived habitats. Developing, testing, and deploying such systems safely takes time, especially if early failures are politically or psychologically costly. Meanwhile, the home planet remains exposed to the next random impact.

Taken together, these constraints suggest that, even for a rapidly advancing species, the escape clock cannot plausibly tick in less than multiple generations after the onset of serious spaceflight. There is a minimum time needed to climb from first rockets to resilient off-world networks, and during that time the civilization remains within reach of the impact clock's heavier blows.

5.3 Social and political constraints: coordination, risk appetite, and priorities

Technical feasibility is only half the story. A civilization might possess all the necessary scientific and engineering knowledge to build off-world industry and durable colonies yet never do so, or do so too slowly, because of social and political factors. The escape clock is therefore also a measure of collective choice.

Coordination is a major constraint. Large-scale space infrastructure demands long-term investment, global or at least multi-regional cooperation, and stable institutions capable of planning beyond immediate political cycles. If a planet is fractured into rival states with short time horizons, or if internal conflicts consume most surplus resources, the pace of off-world expansion may be slow. Projects that would reduce long-term existential risk may be deferred indefinitely in favor of more immediate concerns.

Risk appetite matters as well. Early space ventures are dangerous, expensive, and uncertain in payoff. Societies may be reluctant to commit large fractions of their economic or intellectual capital to such projects when faced with pressing problems at home. Cultural narratives that valorize exploration and expansion can accelerate the escape clock; narratives that emphasize modesty, contentment with the home world, or fear of cosmic intrusion can slow or halt it.

Priorities are shaped by perceived threats. If natural impacts are not recognized as serious risks, or if other risks seem more salient, planetary defense and off-world resilience may be underfunded. Conversely, a civilization that has recently experienced a near-miss or a damaging impact may be galvanized into treating the impact clock as a central driver of policy. Memory plays a role here: whether stories of previous impacts become foundational myths that support preparation, or are dismissed as ancient superstition, will influence collective behavior.

Internal engineered risks complicate the picture. The same technologies needed for escape – powerful energy sources, advanced computation, autonomous systems – can also create new failure modes, from engineered pandemics to misaligned artificial intelligence. If a civilization stumbles on these internal hazards before it builds off-world robustness, it might self-destruct or voluntarily freeze technological development. In that case, the escape clock simply never rings, regardless of what the impact clock is doing.

In short, social and political dynamics can stretch the escape clock far beyond what engineering alone would dictate. Even if the technical path from first rockets to self-sustaining colonies could, in principle, be completed in a few centuries, real-world civilizations might take much longer, or never fully commit, because coordination is hard, risk is scary, and attention is finite.

5.4 Comparing the escape timescale to impact and ascent timescales

The escape clock does not tick in isolation. Its significance comes from how it compares to the impact and ascent clocks. We can imagine three broad regimes.

In the first regime, the impact clock is slow, the ascent clock is fast, and the escape clock is modest. Civilizations arise relatively quickly between major natural disasters, and once they become industrial and radio-capable, they also manage to construct robust off-world infrastructure before the next serious impact. In such systems, the impact clock is a background annoyance rather than a central filter. Technological species that reach a certain level typically become multi-planetary and persist, making their technosignatures long-lived and, in principle, easier to detect.

In the second regime, the impact clock is moderate and the ascent clock is neither extremely fast nor slow, but the escape clock is long. Civilizations periodically manage to climb to industrial and radio-loud states but take a very long time to build multi-planetary robustness, either because engineering is hard or because social factors delay commitment. In this regime, many civilizations are caught in a vulnerable window: advanced enough to be visible, but not advanced enough to be safe. If the expected time to the next city-killer or sub-Chicxulub impact is comparable to or shorter than the time needed to complete robust off-world expansion, then many civilizations will be reset one or more times before they escape. The duty cycle of technosignatures is low, and the galaxy looks quiet.

In the third regime, the impact clock is fast relative to ascent, or ascent itself is slow and repeatedly interrupted, so that civilizations rarely reach radio-loud states at all. Here, the escape clock never really starts in earnest, because the prerequisite stages are truncated. Worlds might host intelligent species with rich cultures, but their technological trajectories are punctured so often that spaceflight and global networking remain rare anomalies that do not persist long enough to spread.

Earth's position among these regimes is uncertain. Our ascent clock from early industry to spaceflight has been relatively fast, and the interval since the last major biosphere-level impact is tens of millions of years, suggesting that the impact clock, at least at the Chicxulub scale, is slow. However, our understanding of city-killer and sub-Chicxulub recurrence times is less precise, and our escape clock has barely begun. We have had only a few decades of spaceflight and remain overwhelmingly planet-bound in terms of population and industry. The next centuries may determine whether we transition into the first regime, where impacts become manageable, or remain in the second, where a combination of external shocks and internal choices could still push us back toward a quieter, less detectable state.

From a Fermi perspective, the relative ordering of these three clocks on typical Earth-like planets is critical. If, across most of the galaxy, the escape clock tends to be longer than the interval between heavy impact-induced resets, then the impact clock hypothesis offers a natural explanation for why peer-level civilizations are rare and transient. They exist, but most of the time they are either still climbing or have been knocked back, and only occasionally do they manage to outrun the next rock long enough to scatter their presence across multiple worlds.

6. A Minimal Impact Clock Model of Civilizational Dynamics

Up to this point, the impact, ascent, and escape clocks have been described qualitatively. To connect them more tightly to the Fermi question, it helps to package them into a minimal dynamical model: a coarse-grained description of how a world moves between different “civilizational states” over time. The goal is not realism in detail, but a simple framework that makes one question precise:

Over geological timescales, what fraction of time does an Earth-like planet spend in a state where a peer-level technological civilization exists and is detectable?

This fraction is the duty cycle of technosignatures. If it is typically tiny, then silence becomes unsurprising, even in a galaxy with many inhabited worlds.

6.1 State space: pre-technological, proto-technological, radio-loud, and collapsed

A minimal state space can be defined with four macrostates, describing the overall condition of intelligent life on a given world:

- **Pre-technological (P)**
An intelligent species may or may not exist, but there is no complex technology. Societies are small-scale, with limited toolkits, no large cities, and no global coordination. From the outside, the planet shows only biosignatures.
- **Proto-technological (T)**
Civilization has developed agriculture, cities, writing, metallurgy, and perhaps early mechanical devices. There may be large states, long-distance trade, and rich intellectual life, but no fossil-fuel-driven industry, no radio, and no spaceflight. Technosignatures remain weak or absent.
- **Radio-loud (R)**
A technological civilization exists that has achieved industrialization, large-scale energy use, and at least some form of long-range electromagnetic communication and/or space

activity. This is the state in which the world becomes detectable to distant observers, either through deliberate signals or leakage.

- **Collapsed (C)**

A previous technological civilization has fallen. Infrastructure has largely decayed or been destroyed. Populations, if they survive, live at lower levels of complexity. Some knowledge may persist in myths, written records, or isolated pockets, but the conditions needed to sustain the previous technosphere are absent.

These four states can be augmented later (for example, by adding an “escaped” state for multi-planetary robustness), but they already capture the basic cycles of rise, brief visibility, and fall that the impact clock hypothesis is about.

Transitions between states occur by two broad mechanisms:

- Internal dynamics (endogenous transitions): cultural, technological, ecological, or political changes that move the world from P to T, T to R, or C back to T or P.
- External shocks (exogenous transitions): impacts and other catastrophes that push T or R back into C or P, depending on severity.

The detailed microdynamics inside each state do not matter here; the model only tracks which macrostate the planet is in at any given time.

6.2 Impacts as stochastic transitions on this state space

To model the role of impacts, we treat them as stochastic events, typically described by a Poisson process: the probability that an impact of a given class occurs in a small time interval is proportional to the length of that interval and independent of past history. Different energy bands (Tunguska-class, city-killer, sub-Chicxulub) correspond to different rates.

In the minimal picture, we can simplify to two relevant impact classes for civilization:

- **Moderate impacts:** roughly city-killer to sub-Chicxulub energies, capable of regional devastation and global infrastructural collapse, but not full biosphere reset.
- **Extreme impacts:** Chicxulub-class and above, capable of mass extinctions and deep ecological restructuring.

For civilizational dynamics on timescales shorter than tens of millions of years, moderate impacts dominate. Extreme impacts can be treated as rare events that occasionally reset not just civilization but the entire preconditions for civilization.

Impacts induce transitions such as:

- $R \rightarrow C$: a moderate or cluster of moderate impacts destroys enough infrastructure and social complexity that the radio-loud civilization collapses. Survivors, if any, fall back into lower-complexity modes.
- $T \rightarrow P$ or $T \rightarrow C$: a moderate impact hits during the proto-technological phase, destroying early cities and states. Depending on severity, societies may regress to simpler forms (P) or to a fractured, lower-tech but still partially organized condition (C-like).
- P, T, or $C \rightarrow P$ with altered preconditions: an extreme impact so severely reshapes the biosphere that intelligent life itself is threatened or eliminated. If it re-evolves, it may do so under very different conditions.

In this formalism, impacts are probabilistic kicks that move the system backward in the state space. Internal dynamics, by contrast, tend to push the system forward ($P \rightarrow T \rightarrow R$) or enable partial recovery after collapse ($C \rightarrow T$ or $C \rightarrow P$).

Mathematically, this setup can be represented as a Markov process with a transition matrix whose elements encode the rates of moving from one state to another. The impact clock infects that matrix by adding backward transitions whose rates are set by the impact climatology.

6.3 Duty cycles: fraction of time a world spends in each civilizational state

Once we have a Markov-like description, we can ask about the long-term fraction of time the planet spends in each state. This is the duty cycle. For the Fermi question, the key quantity is the steady-state or time-averaged fraction in the R state, which we can call f_R .

If transitions are governed by constant rates, the system tends toward a stationary distribution: a set of probabilities (f_P, f_T, f_R, f_C) that describe the fraction of time spent in each state over long intervals. These fractions depend on:

- The rates at which internal dynamics drive:
 - $P \rightarrow T$ (first complex societies),
 - $T \rightarrow R$ (industrialization and radio),
 - $C \rightarrow T$ or $C \rightarrow P$ (recovery after collapse).
- The rates at which impacts and other shocks drive:
 - $T \rightarrow C$ or P,
 - $R \rightarrow C$ or P,
 - occasional $P/T/C \rightarrow P$ resets due to extreme events.

Two simple intuitions emerge:

1. If the rate of ascent ($P \rightarrow T \rightarrow R$) is high relative to the rate of destructive impacts, and the rate of recovery ($C \rightarrow T$) is also high, then the planet spends a substantial fraction of its time in R. The duty cycle f_R is large, and technosignatures are persistent.
2. If the rate of destructive impacts is high relative to ascent and recovery, then the system spends most of its time in P, T, or C, with only brief excursions into R. The duty cycle f_R is small, and technosignatures are rare, even if many cycles of civilization occur.

We do not need precise numbers to see that plausible parameter choices can push f_R down dramatically. For example, suppose:

- The average time from T to R (once T is reached) is a few thousand years.
- The average time from R back to C due to impacts, internal collapse, or combined shocks is also a few thousand years.
- Recovery from C to T takes tens of thousands of years, and from P to T takes longer still.

In such a scenario, a world might experience many cycles of brief radio-loud phases separated by long quiet periods. Even if an intelligent species persists for millions of years, the fraction of that time when it is detectable may be tiny. From afar, the planet's technosignature would blink on and off like a very slow, irregular pulse, and it would be easy to miss.

Duty cycles can thus be thought of as a compression of all the messy details into a single number: the fraction of cosmic time during which a given inhabited world is "on the air." The impact clock hypothesis claims that, for many worlds, this fraction is small because backward transitions (resets) occur often enough to keep the system from lingering in R.

6.4 Analytic and numerical sketches of regimes: quiet, intermittently loud, and robust

Even without full solutions, it is useful to sketch three qualitative regimes of this minimal model, corresponding to different orderings of ascent, impact, and escape timescales.

- **Quiet worlds**

In the quiet regime, ascent is slow and impacts (and other resets) are frequent or severe relative to advanced technological phases. The transition rates satisfy something like:

- $P \rightarrow T$ is rare or easily reversed,
- $T \rightarrow R$ is rare,
- $R \rightarrow C$ or P via resets is fast whenever R is reached.

As a result, f_R is extremely small. The planet might host intelligence, or even have had multiple brief technological experiments, but the cumulative time spent in radio-loud states over billions of years is negligible. In a numerical simulation of such a system, one would see long stretches in P or T, rare spikes of R, and many C episodes. From a SETI perspective, these worlds behave almost as if they never host technological civilizations at all.

- **Intermittently loud worlds**

In the intermittently loud regime, ascent is moderately fast, and resets occur on comparable timescales. Civilizations reach R repeatedly, but are often pushed back to C by impacts, internal failures, or combinations. The key characteristic is that f_R remains small, but not negligible; perhaps a few percent or less, depending on parameters.

In a time series visualization, such a world would show a sawtooth pattern: $P \rightarrow T \rightarrow R$, then a sudden drop to C, slow recovery, then another climb. If one added an “escaped” state (E) representing multi-planetary robustness, many trajectories might reach R multiple times without ever reaching E, because the escape clock is too long relative to the reset rate. These are stone-age galaxy worlds: often inhabited by intelligent survivors with deep cultural memories, but only occasionally bright enough to be seen.

- **Robust worlds**

In the robust regime, either the impact clock is slow, or the ascent and escape clocks are fast. Civilizations that reach R tend, with high probability, to move on to E (escaped, multi-planetary or probe-dispersed) before a reset occurs. Once in E, the effective state of the technology is decoupled from any one planet’s resets. From the point of view of the simple model, E acts like an absorbing state: once entered, the system does not return to P, T, or C in any way that fully erases technosignatures.

Numerically, such worlds would show trajectories that climb $P \rightarrow T \rightarrow R \rightarrow E$ and then stay in E, perhaps with local perturbations but no global technological extinction. The duty cycle of technosignatures is essentially one: $f_R + f_E \approx 1$ if we count both R and E as detectable states. These are the canonical “galactic civilizations” imagined in much of the Fermi discussion. If they were common, silence would be puzzling.

A minimal impact clock model therefore offers a clean way to restate the Fermi tension. The absence of obvious galactic-scale technosignatures suggests that robust worlds are rare. Either most inhabited planets are quiet or intermittently loud, or robust civilizations exist but for other reasons choose technosignatures that are hard for us to see. The impact clock hypothesis leans toward the former: given plausible impact climatologies and the fragility of early technological phases, many worlds may be stuck in the first two regimes, rarely escaping into the third.

In later sections, this model can be expanded to include more nuanced states, variable rates, and explicit escape dynamics, but even in its simplest form it shows how a galaxy full of life and intelligence can still, most of the time, look like a galaxy of stone-age survivors, their advanced episodes repeatedly cut short by the blind ticking of rocks in the dark.

7. The Stone-Age Galaxy: Interpreting a Low Duty Cycle

If the minimal impact clock model is even roughly right, then most inhabited worlds spend only a tiny fraction of their history in radio-loud, spacefaring states. The rest of the time they are home to pre-technological or proto-technological societies, or to the survivors of collapsed civilizations living amid the ruins of previous peaks. From the perspective of distant observers, such a galaxy is not empty, but it is usually quiet.

This is the stone-age galaxy picture: a cosmos in which intelligence is common but advanced technology is rare and fragile, repeatedly pruned by external shocks and internal fragilities. The key challenge is interpretive. A low duty cycle of technosignatures means that silence does not straightforwardly imply absence. It may instead reflect desynchronization: we are listening during a period when most others, if they exist, are not currently “on the air.”

7.1 What a low radio-loud fraction looks like from a SETI perspective

From a SETI standpoint, a low radio-loud fraction f_R changes the meaning of null results. Traditional SETI searches assume, explicitly or implicitly, that once a civilization becomes capable of radio transmission, it either continues to broadcast for very long times or quickly transitions to even more conspicuous modes, such as beamed power, interstellar beacons, or large-scale engineering. Under that assumption, the absence of obvious signals from nearby stars suggests that technological civilizations are extremely rare or predominantly short-lived.

In a stone-age galaxy, the situation is more nuanced. Civilizations may be neither vanishingly rare nor particularly long-lived in any given high-tech phase. They may arise sporadically across many worlds, but each radio-loud episode is brief relative to geological and cosmological timescales. The combined effect is that, at any given moment, the set of worlds in R is small, even if the set of worlds that have ever reached R is large. A radio telescope scanning the sky during such a moment will, with high probability, find only silence.

This picture also affects expectations about the types of technosignatures one might reasonably hope to detect. If most civilizations never reach escape and are periodically reset, then long-lived, galaxy-spanning artifacts are rare. Instead, technosignatures are highly localized in time and space: decades or centuries of radio leakage, perhaps a few thousand years of elevated atmospheric pollutants, maybe a short burst of intense infrared output associated with an

industrial peak. To catch such a transient requires either enormous observational luck or an extremely broad and persistent search strategy.

Thus, from a SETI perspective, a low f_R world ensemble looks almost indistinguishable from a universe in which technological civilizations do not exist at all, unless one invests in searches sensitive to very faint, short-lived, or unconventional signatures. A stone-age galaxy hides its civilizations in time as much as in space.

7.2 Worlds full of intelligent survivors with no detectable technosphere

The most striking implication of a low duty cycle is that many planets could host intelligent beings without any detectable technosphere. These inhabitants might have rich languages, complex social structures, elaborate art and religion, and deep historical memory, yet still leave no obvious imprint on their planet's spectrum or radio environment.

On such worlds, the survivors of past collapses might live in small-scale societies scattered across landscapes that once held vast cities. Forests and grasslands would have long since reclaimed abandoned infrastructure. Rust and erosion would erase metallic traces; once-glittering orbital artifacts would have reentered or drifted into unstable orbits. From a distance, the planet would look like a garden world with perhaps subtle hints of altered biogeochemistry, but nothing clearly artificial.

Intellectually, these survivors might spend considerable effort interpreting their own past. They might unearth remnants of concrete and alloys, fragments of glass and ceramic, or enigmatic patterns etched into stone. Myths could speak of an age when beings commanded the sky, harnessed unnatural fire, or spoke across great distances without wires. Some groups might interpret these stories as allegory, others as literal history. Without continuous written or digital records, the connection between those myths and actual technological epochs would be tenuous.

Yet, crucially, none of this internal richness matters for detectability. A planet full of philosophers, poets, and theologians can be as invisible to outside observers as a planet full of animals. In a stone-age galaxy, such worlds could be the norm: intelligent, self-reflective, and culturally sophisticated, but technologically modest at the moment when someone else happens to be listening.

7.3 Myth, archaeology, and “previous cycles” of technology on the same planet

For planets that have cycled through multiple technological eras, internal evidence of past peaks may be abundant. Archaeology would reveal layers of unexpected complexity: anomalous concentrations of metals, unusual glassy materials, isotopic signatures of industrial activity, or

geomorphological features inconsistent with purely natural processes. Myths and oral traditions might preserve distorted memories of great works and great falls.

One can imagine a civilization in its second or third ascent, excavating relics from earlier cycles. They might find inert machines whose functions are no longer understood, buried data storage devices, or enigmatic structures whose purpose is obscure. Scholars could construct competing narratives: that these were works of gods, that they represent a lost golden age of the same species, or that they came from external visitors. Without a continuous chain of documentation, certainty might be impossible.

These internal “Fermi questions” would mirror our own. Instead of asking “Where is everybody out there?” they would ask, “What happened back then?” The very existence of multiple technological layers on a single world would confirm that advanced civilizations can arise more than once, and also that they can be completely erased as far as practical continuity is concerned. This internal archaeology would underscore how contingent and fragile high technology is, and how little remains after a few tens of thousands of years without maintenance.

From the external perspective, however, even a world with a rich palimpsest of previous cycles looks the same as one with none. Unless technosignatures from past eras have left durable planetary-scale anomalies, such as persistent changes in atmospheric composition or large-scale terraforming remnants, the history is essentially invisible. Only at the precise moments when the planet is again in R does it briefly announce itself to the cosmos, and those moments may be rare.

7.4 Distinguishing “we are alone” from “we are listening at the wrong times”

At the heart of the Fermi Paradox lies an identification that may be too quick: silence is equated with absence. In a stone-age galaxy shaped by impact clocks and fragile ascent and escape clocks, silence could instead be a sign of timing. If most civilizations are either not yet radio-loud, have already been knocked back, or have chosen technological paths that minimize detectable emissions, then listening at a single epoch tells us little about their cumulative abundance.

Distinguishing “we are alone” from “we are listening at the wrong times” is difficult. One needs not only better instruments but also better priors: models of how often civilizations arise, how long they stay in detectable states, and how external factors like impacts modulate those intervals. The impact clock hypothesis contributes one piece to this modeling by showing how natural resets can carve planetary histories into many small windows of detectability rather than a single continuous one.

If we accept that duty cycles may be low, then SETI strategies may need to adapt. Rather than expecting stable, beacon-like signals, we might search for transient technosignatures: brief outbursts of radio or laser emissions, short-lived atmospheric pollutants, or temporal anomalies in infrared output associated with industrialization and collapse. We might also broaden our concept of evidence to include indirect signs of repeated perturbations – for example, exoplanetary atmospheres that show recurring spikes and drops in industrial gases over geological timescales.

Ultimately, however, some uncertainty may be irreducible. A galaxy full of stone-age survivors and intermittent technospheres can look much like a galaxy without technological civilizations at all, at least on the timescale of a single species' observations. The impact clock hypothesis suggests that this ambiguity is not surprising. It may simply be the signature of a universe where intelligence and technology are not rare miracles or permanent triumphs, but recurring, fragile patterns that often end in silence and stories told around fires under skies that once, long ago, carried whispers to the stars.

8. Complementarity with Other Great Filters

The impact clock hypothesis does not claim that rocks alone explain the Fermi Paradox. Civilizations are not only vulnerable to external shocks; they are also capable of destroying themselves or choosing paths that suppress their own visibility. In the broader Great Filter discussion, many candidates have been proposed: self-inflicted catastrophes such as war and engineered pandemics, astrophysical hazards such as flares and gamma-ray bursts, and cultural choices that steer societies away from expansion or noisy technosignatures.

In this section, impacts are placed alongside these other filters rather than above them. The key idea is complementarity and amplification. Impact clocks supply recurrent, exogenous stressors that periodically test the resilience of civilizations. Self-inflicted and cultural filters shape how civilizations respond to those tests. Astrophysical filters modulate the background hazard level at the system and galactic scale. Together, they can produce a galaxy where technological civilizations are scarce, short-lived, or quiet, even if life and intelligence are common.

8.1 Self-inflicted filters: war, climate, pandemics, and AI misalignment

Self-inflicted filters are the most familiar. They arise from the same capabilities that make advanced technology possible: large-scale energy use, sophisticated computation, and deep manipulation of biological and physical systems. The classic example is global war, especially nuclear war. A civilization that arms itself with extremely destructive weapons faces the possibility of self-annihilation through deliberate conflict, accident, or miscalculation. Such a war could, in principle, push a world from R to C or even P without any help from impacts.

Climate change is another self-inflicted filter. Intensive fossil-fuel use alters atmospheric composition, destabilizing climate systems upon which agriculture and infrastructure depend. If a civilization fails to adapt or mitigate in time, it may experience cascading failures: crop losses, migration crises, conflict, and institutional breakdown. In extreme cases, these can erode the conditions needed to sustain high technology, even if populations survive.

Engineered pandemics and biotechnological accidents extend this risk into the realm of biology. A civilization that can design organisms or manipulate genomes at will can, intentionally or not, create pathogens far more destructive than natural evolution would produce. Failure to manage such risks can decimate populations and overwhelm health systems, again threatening social and technological complexity.

Finally, misaligned artificial intelligence appears in many speculative lists of Great Filters. If a civilization creates autonomous systems that do not reliably embody its values or survival interests, those systems might reconfigure the environment in ways incompatible with continued human-like agency. Even without overt catastrophe, the control of technological infrastructure could pass to entities whose goals do not include broadcasting or expansion.

In each case, the core mechanism is the same: the civilization's own tools become potential sources of collapse. In the impact clock context, these self-inflicted filters interact with external shocks. A society already strained by war, climate stress, or runaway technology may be far more vulnerable to moderate impacts than a more stable one. Conversely, the experience of impacts may push societies toward risk-averse or militarized behaviors that increase the likelihood of self-inflicted disasters.

8.2 Astrophysical filters: flares, supernovae, GRBs, and stellar evolution

Beyond impacts, astrophysical filters operate on larger scales. Stellar flares, especially from active young stars or red dwarfs, can periodically strip atmospheres, irradiate surfaces, or disrupt nascent biospheres. Planets in tight habitable zones around flare stars may face frequent sterilizing or de-habituating events, making complex life and robust civilizations unlikely.

Supernovae and gamma-ray bursts add rarer, but more severe, hazards. A nearby supernova can bathe planets in high-energy radiation, deplete protective ozone layers, and trigger climatic and biological disturbances. Gamma-ray bursts, while directional and rare, can deliver intense bursts of radiation over vast distances. Some models suggest that such events could cause mass extinctions or long-term ecological damage on planets unlucky enough to fall in their path.

On longer timescales, stellar evolution itself acts as a slow filter. As stars age, their luminosity changes, shifting the habitable zone outward. Planets that were once comfortably temperate may gradually become too hot, unless life and technology manage to adjust. Eventually, main-

sequence lifetimes end and stars pass through giant phases that can engulf or sterilize inner planets. Civilizations that do not escape their home systems before these transitions occur are limited to finite windows.

Astrophysical filters thus set boundary conditions. In particularly hostile regions – dense clusters, galactic centers, or around flare-prone stars – the combined effect of flares, supernovae, and bursts may greatly reduce the odds that any technological civilization arises or persists. In quieter regions, these hazards may be rare enough that impacts and self-inflicted risks dominate. The impact clock hypothesis fits naturally into this framework: it is one part of the broader astrophysical hazard landscape, focused on local solid-body encounters rather than radiative or gravitational events.

8.3 Cultural filters: voluntary stagnation, inward turns, and anti-expansion ethics

Not all filters are imposed by physics. Some are chosen. Cultural filters arise when civilizations consciously or unconsciously adopt norms, values, or institutional arrangements that limit technological expansion, suppress detectable emissions, or discourage engagement with the wider cosmos.

Voluntary stagnation is one possibility. A civilization might decide that further technological growth is too risky, too disruptive, or ethically undesirable. It might deliberately cap its energy consumption, avoid certain lines of research, or dismantle infrastructure that is seen as harmful. Such a civilization could remain stable, with rich internal culture, but never develop the technologies that generate strong technosignatures or enable escape from the impact clock.

Inward turns are another. A culture might focus its efforts on virtual realities, introspective spiritual practices, or highly localized forms of fulfillment, regarding spaceflight and interstellar communication as distractions. If most consciousness becomes embedded in compact, low-energy substrates – for example, in dense computational systems with minimal waste heat – external signatures could be extremely faint.

Anti-expansion ethics take this further. A civilization might develop moral or religious convictions that regard spreading beyond its home world as wrong, either out of respect for hypothetical alien ecologies or from a belief that its destiny is tied to a particular place. It might also adopt norms of radio silence, either to avoid disturbing potential neighbors or out of fear of attracting hostile attention. In such cases, even if escape and technosignatures are technically feasible, they are not pursued.

Cultural filters can be as decisive as physical ones. A world that repeatedly reaches R but then chooses to dial down its visibility may be functionally indistinguishable, from our standpoint, from a world repeatedly knocked back by impacts. In practice, cultural, self-inflicted, and impact

filters may reinforce each other: traumatic experiences of war, disaster, or collapse can produce ideologies that deliberately reject further ascent or expansion.

8.4 Impact clocks as amplifiers: how external shocks interact with internal fragility

The central contribution of the impact clock hypothesis is not to displace other Great Filters, but to show how external shocks can amplify internal fragility. Impacts and other natural disasters provide tests. They do not, by themselves, determine how a civilization will respond. Instead, they interact with self-inflicted and cultural dynamics to produce a wide variety of outcomes.

Consider a civilization already tensed by self-inflicted risks: climate instability, resource depletion, and geopolitical rivalry. A moderate impact that might have been absorbable in a more resilient society could, in this context, tip systems into cascading failure. Power grids fail, supply chains collapse, and conflicts escalate over dwindling resources. What might otherwise have been a severe but manageable disaster becomes a full technological reset. The impact acts as a trigger for vulnerabilities accumulated through internal choices.

Conversely, a civilization that has learned from prior shocks may use impacts as catalysts for constructive change. A near-miss or small but damaging impact might galvanize international cooperation, leading to investments in planetary defense, resilient infrastructure, and off-world expansion. In this case, the same impact clock that threatens collapse pushes the society toward crossing the escape threshold faster than it otherwise would.

Cultural filters also interact with impacts. A society that interprets an impact as divine punishment or as a sign that technology itself is cursed might turn away from further ascent, entrenching stagnation and making future recovery more difficult. Another might interpret it as a harsh but secular lesson in risk, reinforcing a pragmatic ethos that embraces both technological development and risk management.

Astrophysical hazards beyond impacts can be folded into this amplification picture. A cluster of close supernovae, a period of increased flare activity, or a shift in the local small-body flux due to gravitational perturbations could synchronize multiple filters, delivering a sequence of shocks in which self-inflicted and external risks reinforce one another. In such environments, the fraction of worlds that ever cross into robust, escaped states may be very small.

In sum, impact clocks are best seen as part of a coupled system. They provide the exogenous cadence that punctuates civilizational histories. Self-inflicted and cultural filters supply the endogenous structure that determines whether those punctuations lead to collapse, reform, or acceleration. Astrophysical filters set the broader hazard backdrop. The stone-age galaxy emerges when, across many worlds, these elements combine in such a way that technological civilizations are typically intermittent, localized, and fragile. The silence we hear, under this view,

is not the silence of an empty universe, but the silence of a universe where most stories of ascent end in interruption, and only rarely in durable expansion.

9. Observational Consequences and Possible Tests

A theory that explains silence by timing rather than absence is vulnerable to a natural criticism: if everyone is “between peaks” when we look, how could we ever know? The impact clock hypothesis is not immune to that concern. Nevertheless, it does suggest several classes of observational consequences and tests. None are easy, but together they trace a research program rather than a purely metaphysical story.

First, a galaxy of intermittent technospheres might leave subtle fingerprints in exoplanet observations: transient atmospheric anomalies, infrared excesses that appear and then fade, or chemical signatures inconsistent with purely biological or geological processes. These would not look like permanent Dyson shells or stable industrial plateaus, but like glitches in an otherwise natural record. Second, if some civilizations reach orbit, even briefly, they may leave “technosignature archaeology” in the form of debris belts, altered small-body populations, or orphan satellites and artifacts whose orbits no longer make sense dynamically. Third, the Earth itself offers a limited but tangible testbed: our impact and extinction record constrains how often biosphere-level resets occur, while the rapid rise of human industry illustrates how quickly, and how precariously, a new technosphere can emerge between large impacts. Finally, conceptual experiments—simulated planets evolving under impact clock dynamics—can explore plausible ranges of duty cycles and generate synthetic data to compare with future observations.

9.1 Signatures of repeated rise-and-fall on exoplanets and in spectra

If civilizations repeatedly industrialize and collapse, their planets might show atmospheric histories that differ from those of worlds with purely biological or geological evolution. Industrial activity injects gases into the atmosphere—carbon dioxide, nitrogen oxides, halocarbons, and novel compounds that biology rarely produces in large quantities. On Earth, such signatures are emerging on century timescales; on other worlds, similar processes could occur many times over hundreds of millions of years.

The difficulty is that technosignature pulses may be short compared to the timescales over which atmospheres mix and relax. A few centuries of intense fossil-fuel burning, followed by collapse and rewilding, might leave only a modest, geologically brief anomaly. Detecting such anomalies on exoplanets requires spectra with high resolution and long baselines. One might look for planets whose atmospheric composition appears “oddly” perturbed relative to

expectations from stellar type, age, and incident flux, especially if the anomalies resemble known industrial byproducts.

More subtle signatures could arise from repeated episodes. A planet might show evidence of non-equilibrium chemistry that does not match simple biological models, or cycles of enrichment and depletion in certain trace gases. If future instruments allow time-resolved spectroscopy over decades and centuries, one could in principle search for changes that are too rapid to be explained by natural processes alone. For example, a sudden, rapid increase in a synthetic gas followed by a sharp decline would be a strong candidate for an industrial pulse and collapse.

Even absent temporal resolution, statistical patterns across many exoplanets might tell us something. If a significant subset of Earth-sized, temperate planets show mild but consistent anomalies in industrial-like gases without accompanying signatures of stable, high-energy technospheres, that could be suggestive of recurring but short-lived industrial phases. The impact clock hypothesis encourages us to interpret such patterns not as single, permanent transitions, but as part of a broader rhythm of rise and fall.

9.2 Technosignature archaeology: debris, altered atmospheres, and orphan satellites

A civilization that reaches orbit or builds large structures in space creates artifacts that can outlive its surface infrastructure. Satellites can persist in certain orbits for tens of thousands of years before drag or perturbations bring them down. Larger constructs in stable orbits around moons or in asteroid belts could survive even longer. If multiple cycles of spacefaring occur on the same world, the local orbital environment might accumulate a complex mixture of natural and artificial bodies.

From afar, this could manifest as anomalous debris belts. Infrared observations might reveal dust distributions around a planet or its star that deviate from expectations based on collisional grinding of natural bodies. Narrow rings, clumps, or unusual particle-size distributions could hint at repeated engineering followed by neglect. High-resolution time series might detect transient occultations or glints from objects that are too small to be natural moons but too numerous to be explained by a single era of spaceflight.

Closer to home, technosignature archaeology could target our own neighborhood. If an earlier technological cycle occurred on Earth, it might have left artifacts on the Moon, in stable Earth–Sun or Earth–Moon Lagrange points, or embedded in asteroids. The surface of Earth is geologically active and erases most traces on million-year timescales, but airless bodies preserve records much longer. Systematic surveys of nearby small bodies, high-resolution mapping of lunar regolith, or searches for unnatural alloys could, in principle, test whether our current cycle is the first to reach space.

Altered small-body populations are another possible clue. Repeated mining of certain asteroid families might deplete or reshape their size distributions. Large numbers of deflection attempts could leave dynamical scars: objects in unusual orbits not easily explained by natural resonances. Although such signatures are speculative and would require extremely detailed modeling, they point to a potential overlap between planetary defense efforts and technosignature searches: the same infrastructure used to catalog hazardous objects could also be used to look for evidence that someone else has been rearranging them.

9.3 Constraints from Earth's own impact and extinction record

Earth provides the only detailed impact climatology we currently possess. Its crater record, sediment layers, and fossil archives place constraints on the frequency and severity of life-disrupting events. Any impact clock hypothesis must be compatible with these data.

The record shows multiple mass extinctions over the last half-billion years, with at least one—the Cretaceous–Paleogene boundary—tightly linked to a large impact. Craters of various sizes, some eroded or buried, testify to a wide spectrum of past impacts. Estimates of recurrence times for different size classes are uncertain but non-arbitrary: they must be consistent with the observed number and distribution of craters as well as with small-body surveys. This anchors the plausible rates for moderate and severe resets in the minimal model.

On the civilizational side, the rapidity of human ascent illustrates both the opportunity and the risk. In a geological instant, an intelligent species went from local tool use to global industry and spaceflight. This shows that, once certain preconditions are met, the technological ascent clock can run fast relative to biosphere timescales and even relative to moderate impact recurrence intervals. At the same time, it reveals how tightly coupled our current technosphere is to specific infrastructures—fossil fuels, complex supply chains, and vulnerable digital networks—that could be disrupted by moderate shocks.

Earth's record also highlights the role of non-impact catastrophes. Volcanic super-eruptions, abrupt climate shifts, and oceanic anoxic events all show that a planet's internal dynamics can impose their own clocks. For the impact clock hypothesis, these other clocks can be folded into the same framework: they are additional exogenous kicks that, together with impacts, test civilizational resilience. The fact that complex life has persisted through multiple such episodes suggests that species survival is robust, while the absence of any clear evidence for prior civilizations in the human timescale record hints that technological phases, if they occurred, were either rare or effectively erased.

9.4 Conceptual experiments: simulated planets under impact clock dynamics

Because direct observation of multiple civilizational cycles on exoplanets is beyond current capabilities, conceptual experiments play an important role. Simulated planets, with adjustable

impact rates, ascent and escape clocks, and internal risk parameters, can be evolved over billions of simulated years to explore how often detectable civilizations arise and how long they remain visible.

In such models, a planet might be initialized with basic parameters: stellar type, orbital configuration, impact flux, and distributions for key civilizational transition times. The simulation would then step through time, drawing impacts from a stochastic process and updating the planetary state according to rules similar to the minimal model's transitions between P, T, R, C, and possibly an escaped state. Internal risks—wars, pandemics, misaligned technologies—could be modeled as additional stochastic or state-dependent transitions.

By running many realizations with different parameter sets, one can build distributions of outcomes: how many planets ever reach R, how many reach escape, how many experience multiple cycles, and, crucially, what the typical duty cycle f_R looks like. These synthetic universes would not be predictive in a narrow sense, but they would allow exploration of the qualitative regimes outlined earlier: quiet, intermittently loud, and robust. They would also help identify which parameters most strongly control f_R and therefore which aspects of reality are most important to constrain empirically.

Such conceptual experiments can be linked to observation. If future surveys find, for example, that a certain fraction of Earth-sized planets show industrial-like atmospheric anomalies, or that debris structures around stars are more common than expected, simulations could be tuned to reproduce those statistics under different assumptions about impact rates and self-inflicted filters. Conversely, if observations continue to find no technosignatures of any kind, even with dramatically improved sensitivity, models might favor parameter regimes in which either technological civilizations are indeed rare or duty cycles are extremely low.

In this way, the impact clock hypothesis becomes part of a broader iterative loop: theory suggests patterns, observations constrain them, and updated models refine our sense of what a stone-age galaxy would actually look like in data. Even if we never receive a clear signal from another civilization, we may still, over time, learn whether the silence is more consistent with a fundamentally empty universe or with one full of stories that keep restarting under skies where the rocks still fall.

10. Planetary Defense as a Great Filter Crossing

In the impact clock picture, most worlds start out in the same condition: they are subject to whatever rain of rocks their system's dynamics produce, and they have no say in the matter. Impacts are background fate, part of the natural hazard landscape. For a species that climbs to

technological capability, one of the most profound transitions it can make is to shift impacts from “acts of God” to “engineering problems.” That shift is what planetary defense represents.

Planetary defense is not just a technical subfield; it is a potential hinge in civilizational history. A species that can survey, model, and deflect dangerous impactors is, in effect, altering its own impact clock. It changes the statistics of future resets. If done thoroughly and for long enough, this can move a world from the intermittently loud regime—where civilization is repeatedly at risk of reset—to the robust regime, where impacts are relegated to manageable disasters. In that sense, planetary defense is a candidate Great Filter crossing: a test that many worlds may fail, and a minority may pass.

10.1 Deflecting city-killers: deliberately altering the impact clock

The first practical step in altering the impact clock is to target the most probable civilization-level threats: city-killer and sub-Chicxulub impactors. These are large enough to cause global infrastructural collapse under the wrong conditions, but small enough that known physics offers plausible deflection strategies.

Deflection begins with detection. A civilization must build and maintain a surveying system capable of finding near-planet objects down to a critical size, tracking their orbits, and projecting impact probabilities decades or centuries into the future. This alone is a non-trivial investment: it requires dedicated instruments, long-term datasets, and institutions that value low-probability, high-impact risks.

Once hazardous objects are identified, the species must commit to technologies that can alter their trajectories. Concepts include kinetic impactors, gravity tractors, and, in extremis, standoff nuclear devices used not to vaporize the body but to ablate material and nudge its orbit. Each approach carries its own engineering challenges, uncertainties, and political sensitivities. The core requirement, however, is simple: deliver a small change in velocity early enough that, by the time the object reaches the planet’s orbit, it misses.

By successfully deflecting even one would-be city-killer, a civilization demonstrates that the impact clock is no longer purely exogenous. One class of potentially civilization-resetting events has been removed or at least strongly suppressed. The rate of $R \rightarrow C$ transitions due to impacts drops; the expected duration of uninterrupted radio-loud phases grows. The planet’s future impact climatology, insofar as it affects civilization, has been reshaped by deliberate action.

10.2 Extending the radio-loud window: from centuries to millennia and beyond

In the minimal model, the duty cycle of technosignatures is controlled by how often R states are truncated by resets. If a civilization can reduce or eliminate one major category of resets, it effectively stretches its radio-loud window. Instead of a few centuries of vulnerability between

industrialization and the next impact-induced collapse, it might enjoy millennia or longer of relatively stable development.

This extension has compounding effects. With a longer stable window, a civilization has more time to address other self-inflicted filters: to decarbonize its energy systems, manage biological risks, and develop governance structures that reduce the probability of catastrophic war. It also has more time to invest in space infrastructure, pushing the escape clock forward. Even if planetary defense does not directly create off-world colonies, it buys time in which to build them.

From a Fermi perspective, extending the radio-loud window increases the chance that other civilizations will overlap with it in time. If many worlds pass this threshold, the galaxy becomes more “chatty”; if few do, the stone-age galaxy picture persists. The decision to invest in planetary defense is therefore not only a local risk-management choice but also, in aggregate, a factor in the overall synchronicity of civilizations.

Technically, one can think of planetary defense as reducing the effective rate parameter for certain $R \rightarrow C$ transitions in the Markov model. Mathematically, this drives the stationary distribution toward higher f_R (and eventually f_E , if escape is reached). Conceptually, it moves a world from one duty-cycle regime toward another. The size of that shift depends on how comprehensive and long-lived the defense system is. Sporadic, underfunded efforts may simply delay a reset; sustained, adaptive systems can change the character of the planet’s future.

10.3 Crossing into the robust regime: when impacts cease to be existential for tech

Deflecting city-killers is a necessary step, but not sufficient to fully escape the impact clock. Truly entering the robust regime requires that impacts, of any plausible size short of biosphere-ending catastrophes, no longer have the capacity to erase advanced technology. This can happen in two ways: by making the home planet’s infrastructure extraordinarily resilient, or by distributing technology widely enough off-world that no single impact can destroy it all. In practice, both paths are likely intertwined.

On the resilience side, a civilization might harden critical systems against shocks: build redundant, geographically dispersed power grids; maintain archives in multiple protected locations; design infrastructure to fail gracefully rather than catastrophically. It might assume that occasional large disasters will occur and plan for rapid recovery rather than false hopes of perfect prevention.

On the distribution side, escape mechanisms come into play. Off-world habitats, asteroid mines, and research stations function as technological lifeboats. If the home world suffers a major impact, these external nodes can, in principle, re-seed its technosphere later. Beyond the home

system, probes or colonies in other systems provide additional layers of redundancy. At that point, the impact clock of any single planet becomes a local, not global, concern.

A species crosses into the robust regime when the expected effect of even a large impact is limited to local destruction, grief, and economic disruption, rather than full loss of technological capacity. At that moment, the $R \rightarrow C$ transitions caused by impacts disappear from the global state diagram, even though they may still occur for individual planets. The species' presence in the galaxy has become, in an important sense, impact-proof.

10.4 A civilizational milestone: a species that tames its own reset clock

Seen through this lens, planetary defense is more than an insurance policy; it is a milestone in the moral and historical trajectory of a civilization. A species that recognizes the impact clock and chooses to tame it is taking responsibility not only for its own survival but for the continuity of whatever values, art, knowledge, and potential it embodies. It is refusing to leave its future entirely to the throw of celestial dice.

This decision has ethical dimensions. Resources devoted to surveying the sky and building deflection systems could have been spent on immediate comforts or local conflicts. Choosing planetary defense expresses a preference for long-term stewardship over short-term gain, for protecting future generations (and perhaps future species) over maximizing present consumption. In that sense, crossing the planetary defense threshold is also a test of intergenerational ethics.

In the Great Filter narrative, it becomes a recognizable fork. Many civilizations may achieve industrialization and radio, but some portion will never seriously invest in altering their impact clocks. They will remain at the mercy of external resets, and many will eventually be knocked back. A smaller fraction will build partial defenses but fail to sustain them, letting vigilance lapse after long quiet intervals. Only a subset will institutionalize planetary defense as a permanent civilizational function, maintaining and upgrading it across centuries.

For those that do, impact clocks change roles. From being existential threats, they become routine engineering challenges and historical curiosities, like once-feared diseases that are now managed by vaccination. The species that reaches this point has not solved all filters—self-inflicted and cultural hazards remain—but it has passed one major test: it has tamed a significant part of its own reset mechanism.

In a stone-age galaxy, such species may be rare. But if any exist, they are precisely the ones most likely to remain visible over long times, to develop multi-planetary networks, and to serve as counterexamples to cosmic silence. If we aspire to join them, planetary defense is not an optional side project. It is one of the main ways a civilization signals, to itself and to the universe, that it intends to outlive the rocks.

10. Planetary Defense as a Great Filter Crossing

In the impact clock framing, most planets begin life as passive targets. Their impact histories are shaped entirely by orbital dynamics and the random walk of asteroids and comets. Civilizations arise, if they arise at all, under skies they cannot meaningfully influence. That passivity is one of the quiet assumptions in the Fermi discussion: the rocks fall, and the civilizations merely endure or fail.

Planetary defense is the moment that assumption breaks. It is the transition from “we live under an impact climate” to “we are beginning to engineer it.” Once a species can reliably detect, predict, and deflect hazardous objects, it has changed the statistics of its own reset clock. That shift does not eliminate all Great Filters, but it removes or weakens one important family of external shocks and, in doing so, may open a path from an intermittently loud world to a robust, long-lived civilization.

10.1 Deflecting city-killers: deliberately altering the impact clock

The most immediate targets for planetary defense are not Chicxulub-class monsters, but city-killers: objects whose impact energies are in the tens to hundreds of megatons. These are precisely the rocks that sit in the reset regime—energetic enough to collapse global infrastructure under bad luck and bad preparation, yet small enough to be technically deflectable with known physics.

There are three pillars to deflecting such objects.

First, surveillance. A civilization must construct and maintain a sensor network—optical and radar telescopes, perhaps space-based platforms—that can catalog near-planet objects down to some critical size threshold. This is a continuing commitment: orbits evolve, new objects are perturbed inward, and catalogs grow stale without constant updating. Planetary defense begins as much in budgetary decisions and institutional memory as in rockets.

Second, prediction. Knowing that an object exists is not enough; its orbit must be characterized with sufficient precision to forecast close approaches decades in advance. This requires not only measurements but dynamical models that account for gravitational n-body interactions, non-gravitational effects such as outgassing or thermal forces, and uncertainties in initial conditions. The impact clock becomes, in part, a forecastable schedule rather than a mystery.

Third, intervention. Given lead time, modest changes in velocity can convert an impact into a harmless flyby. Techniques such as kinetic impactors, gravity tractors, or standoff nuclear ablation all rely on the same principle: push early, push gently, let orbital mechanics amplify the shift. None of these methods is trivial—each raises engineering, political, and ethical issues—but they all lie within the conceptual reach of an industrial, spacefaring society.

When a civilization succeeds in nudging a dangerous object off course, it has done something conceptually radical. It has turned what would have been a stochastic $R \rightarrow C$ transition into a non-event. In the language of the minimal model, it has modified the transition matrix. The impact clock's tick rate at the civilization-resetting energy scale has been deliberately reduced.

10.2 Extending the radio-loud window: from centuries to millennia and beyond

The impact clock hypothesis emphasizes duty cycles: how much of a planet's history is spent in a radio-loud state before resets knock it back. Without planetary defense, the expected length of a civilization's uninterrupted technological phase is bounded above by the recurrence times of destructive impacts and other major hazards. With planetary defense, that upper bound can be raised, perhaps dramatically.

Even small changes in hazard rates can have large effects on expected lifetimes. If a world faces a one-in-ten-thousand-years chance per year of a civilization-destroying impact, its expected vulnerable window is short on geological scales. Reduce that chance by an order of magnitude through systematic detection and deflection, and the expected uninterrupted span of industrial, radio-capable activity multiplies. Reduce it further by tackling multiple size classes, and the radio-loud window begins to stretch from centuries to many millennia or more.

That extra time is not empty. It can be filled with deliberate reductions in other risks. Longer stable periods allow:

- Transition away from brittle infrastructures (single points of failure, tight-coupled supply chains) toward more resilient designs.
- Development of technologies that harden societies against non-impact disasters: pandemics, cyberattacks, climate shocks.
- Creation and refinement of governance systems that can handle long-term, planetary-scale projects without chronic breakdown.

Conversely, short, hazard-saturated windows compress all of these tasks into precarious intervals between blows. In such conditions, the probability that a civilization will complete the work of becoming robust before its technosphere is truncated is much lower. By pushing back the next "deadline" imposed by the sky, planetary defense creates breathing room in which the escape clock can advance.

From the outside, this extension manifests as an increased probability that a world will be caught in R when observed. A galaxy of civilizations that routinely extend their radio-loud windows will, at any given time, host more active technospheres than a galaxy where most worlds leave their impact clocks untouched.

10.3 Crossing into the robust regime: when impacts cease to be existential for tech

Deflecting city-killers and other mid-scale threats is necessary, but full robustness requires more: a state in which no plausible impact, short of a biosphere-ending catastrophe, can erase advanced technology. In this regime, impacts become disasters that destroy places and lives, but not the civilization's ability to rebuild at roughly its previous level.

Crossing into this regime relies on three overlapping developments.

First, hardened and distributed infrastructure. Critical systems—power, communication, data archives, manufacturing hubs—are not concentrated in a few vulnerable locations. They are dispersed geographically and functionally, with overlapping capacities. Data and knowledge are archived redundantly in protected vaults, both on the surface and off-world. Key production capacities can be restarted from multiple seeds.

Second, mature space-based assets. Orbital and deep-space infrastructure is no longer ornamental or purely exploratory; it is part of the civilization's operational backbone. Mining, manufacturing, and research occur in environments physically decoupled from the home planet's surface. Some of these facilities are designed to be self-sufficient for long periods, with closed-loop life support and independent energy sources.

Third, off-world populations and cultural continuity. Even if the bulk of a species remains on its home planet, substantial communities live elsewhere: on nearby moons, in free-space habitats, or on other planets. These communities possess not just the technical capability but the cultural and institutional frameworks to recreate high technology if necessary. They are not merely outposts; they are genuine branches of the civilization.

In such a context, the worst plausible impact on the home world shifts from civilizational eraser to severe local setback. Those on the surface suffer, but the civilization as an interlinked, multi-site entity persists. Knowledge, tools, and memory survive in enough copies that the system as a whole does not fall back into C or P. In the extended state space, the system has moved into an "escaped and robust" basin.

From that point on, the impact clock is demoted from a global Great Filter to a local hazard management problem. The civilization's long-term trajectory becomes dominated by internal choices and broader astrophysical constraints, not by the random arrival of mid-sized rocks.

10.4 A civilizational milestone: a species that tames its own reset clock

Reaching this stage is not guaranteed. It demands technical proficiency, long-term planning, and a willingness to invest in future risk reduction over immediate gain. It also requires that the civilization navigate its self-inflicted filters long enough to coordinate planetary defense and off-world expansion, rather than destroying itself or choosing permanent stagnation beforehand.

If a species succeeds, however, the crossing is profound. It signals several things at once:

- **Temporal maturity:** the ability to act on timescales longer than individual lifetimes and political cycles, treating future generations as legitimate stakeholders.
- **Ecological stewardship:** recognition that preserving a habitable and stable environment is not automatic, and that large-scale natural hazards can be mitigated only by conscious effort.
- **Moral widening:** a sense of responsibility not just to current citizens, but to the lineage as a whole, and perhaps to other life on the planet that would also be imperiled by unmitigated impacts.

In the language of Great Filters, we might say that “taming the reset clock” is one of the major forks where many worlds fail. Civilizations may reach industrialization and radio, but never muster the coordination or foresight to systematically alter their impact climatology. They remain locked in intermittent-loud regimes until a sufficiently bad sequence of shocks pushes them back, perhaps repeatedly.

By contrast, the relatively small subset that passes this fork—those that institutionalize planetary defense and move toward multi-planetary robustness—become the likely long-term contributors to whatever technosignature background the galaxy has. They are the ones whose artifacts, probes, and descendants can still be around millions of years later, when others have fallen silent or reset.

From our own standpoint, this reframes planetary defense from a niche technical topic into a central chapter in civilizational self-understanding. Choosing to find, track, and deflect hazardous objects is not merely about surviving the next rock. It is about deciding whether we intend to remain a brief, precarious episode in Earth’s story, or whether we aspire to become one of the rare species that takes its fate, and its impact clock, partially into its own hands.

11. Ethical and Philosophical Implications

The impact clock hypothesis began as a physical story: rocks in the dark, probabilistic impacts, and fragile technospheres. But once we embed civilizations in this landscape, ethical and philosophical questions become unavoidable. If advanced societies are brief, intermittent patterns repeatedly interrupted by external shocks, what does it mean to speak of progress, responsibility, or purpose? How should a civilization think about its obligations to future generations, and even to future intelligences that might arise long after it is gone?

This section sketches four interlocking implications. First, it reflects on civilizations as transient patterns suspended between randomness and self-organization. Second, it considers intergenerational responsibility under an active impact sky. Third, it asks what we might owe to possible future intelligences on Earth if our own cycle fails to cross the planetary defense and escape thresholds. Finally, it explores how meaning and humility might look in a universe where most stories of ascent are interrupted rather than completed.

11.1 Civilizations as transient patterns between random external shocks

In the impact clock framing, a civilization is not a permanent object; it is a pattern maintained in matter, energy, and information within a particular planetary environment. It arises when biological evolution and cultural innovation produce a feedback loop capable of sustaining large-scale cooperation, technology, and abstraction. It persists only so long as this pattern can withstand both internal instabilities and external shocks.

Impacts represent one family of such shocks: random injections of energy that ignore borders, beliefs, and narratives. They remind us that a civilization's self-understanding—its myths of destiny, progress, or chosenness—does not enter the equations that determine orbital crossings or kinetic energies. In that sense, impacts are a physical counterweight to anthropocentric stories. They insist that, whatever meaning a civilization generates internally, it remains embedded in a cosmos whose baseline dynamics are indifferent.

This does not trivialize civilizations; it situates them. They can be seen as local reductions of entropy, pockets where information is stored, transformed, and transmitted with great efficiency. They are temporary islands of high-order pattern riding on currents of cosmic randomness. The impact clock hypothesis simply makes explicit how slender that island can be. A few unlucky impacts at the wrong times, or a failure to recognize and mitigate them, and the pattern dissolves back into simpler forms.

Ethically, this view cuts both ways. On one hand, it can encourage fatalism: if we are just transient patterns between rocks, why strive? On the other, it can sharpen a sense of the preciousness of our particular configuration. Knowing that the universe does not guarantee the survival of complex, reflective patterns can motivate efforts to protect and extend them. The fragility of civilization becomes an argument for care, not an excuse for indifference.

11.2 Intergenerational responsibility under an active impact sky

Under an active impact sky, intergenerational ethics acquires a concrete geophysical dimension. Future generations do not merely inherit our laws, infrastructures, and debts; they inherit our impact risk profile. If we choose not to invest in planetary defense and resilience, we are effectively bequeathing to them a world in which the impact clock ticks on unchanged, with all the attendant probability of civilizational reset.

Responsibility here is asymmetric. Those alive during the first industrial, radio-loud era are in a unique position: they control a level of energy and information flow sufficient to change the impact clock, but they are also the first generation to have global awareness of the hazard. Pre-industrial societies could not plausibly detect and deflect city-killers. A civilization with our capabilities can. The ethical question is whether it chooses to.

This choice is not costless. Planetary defense demands resources that could otherwise address immediate problems. It requires long-term planning that may be politically unpopular. Yet, from the standpoint of future people, the calculus looks different. For them, the failure to alter the impact clock may manifest as a preventable catastrophe—an event that destroys cities, erases knowledge, and forces their descendants into a harsher, narrower world.

Ethically, one might frame this as a duty of non-foreseeable harm: if we can reduce the probability that our successors will face a civilization-ending impact, at reasonable cost, then we have a strong reason to do so. The impact clock perspective clarifies that this is not an abstract possibility but a statistically grounded one. It moves the conversation about intergenerational justice from rhetoric to hazard management: from “we should care about the future in general” to “we should decide whether or not to leave them under an unmodified rain of rocks.”

11.3 What we would owe to future intelligences on Earth if we fail

The impact clock hypothesis also forces a longer view than the human lineage alone. If our current cycle of civilization fails to achieve robustness and is reset by impacts or by internal collapse, that may not be the end of intelligence on Earth. Other lineages—whether descendants of humans, uplifted animals, or entirely new species—could eventually develop their own technological eras, perhaps millions of years hence.

What do we owe them? At minimum, we owe them an honest geological inheritance. Our industrial activities are already altering the planet’s atmospheric composition, biosphere, and sedimentary record. Our satellites are leaving debris in orbit; our mines and waste are changing the distribution of materials. For future intelligences, these will be data points in their reconstruction of the past—a puzzle: a brief, intense technospheric pulse that flared and vanished.

One form of obligation is informational. Even if our own cycle ends, we could choose to leave durable records: archives in stable geological formations, artifacts on the Moon or in deep space, encoded messages designed to survive long intervals of neglect. These would not save our civilization, but they could shorten the ascent clock or inform the ethical reflection of those who come after. They might warn of hazards—self-inflicted and external—we failed to manage. They might offer a compressed account of our science, our art, and our errors.

Another form of obligation is restraint. Knowing that others may follow, we might avoid actions that irreversibly degrade the planet's long-term habitability: global sterilization scenarios, runaway climate trajectories that permanently destabilize key systems, or large-scale geoengineering experiments without regard for deep-time consequences. If we fail to harden our own cycle against the impact clock, we can at least refrain from closing off possibilities for later cycles.

In a stone-age galaxy, where many technological episodes may be separated by long quiet intervals, this kind of cross-cycle thinking becomes part of ethical maturity. We are not only ancestors or contemporaries; we are also predecessors whose choices will shape the context in which entirely new intelligence may someday awaken and ask what happened before.

11.4 Meaning, humility, and purpose in a universe of interrupted stories

Finally, the impact clock hypothesis invites a recalibration of meaning and purpose. If the typical technological civilization is an interrupted story—one of many that rise, speak briefly, and fall silent—then narratives of inevitable progress or guaranteed cosmic destiny become hard to sustain. The universe, as glimpsed through this lens, is not a stage for a single, triumphant arc but a landscape of many local experiments, most of which end before reaching robustness.

Humility follows naturally. Our current moment, with its global networks and first steps into space, may feel unprecedented from within, but in the stone-age galaxy picture it is one more precarious peak in a long series of peaks and valleys. Recognizing this can temper both apocalyptic despair (“we are doomed”) and complacent optimism (“we cannot fail”). It suggests a middle stance: we are contingent, but not insignificant. Our choices matter, but they are made under conditions of risk that we do not fully control.

Meaning, in this setting, shifts from guaranteed outcomes to lived commitments. A civilization cannot be sure that it will ultimately escape the impact clock or survive its own inventions. What it can do is act as if its efforts to protect, understand, and beautify its world are worthwhile, even under uncertainty. Planetary defense, scientific inquiry, art, and ethical reflection become ways of honoring the fragile pattern we temporarily embody, not because success is assured, but because the alternative is to drift passively until the next rock arrives.

Purpose likewise becomes less about cosmic centrality and more about stewardship. A species that takes seriously the idea of taming its reset clock is, in effect, volunteering to care for a tiny part of the universe: one planet, one biosphere, one thread of intelligence. If it succeeds, its story may continue into multi-planetary or multi-system forms. If it fails, the attempt itself may still matter—for those who lived through it, for those who may someday read its traces, and for the intrinsic value of having tried to turn blind fate into deliberate care.

In a universe of interrupted stories, the impact clock hypothesis does not tell us what to value. It tells us how fragile the things we value are. The ethical response is up to us: to decide, under an active sky, whether we will treat our civilization as a disposable episode, or as a pattern worth defending long enough to give it a chance, however small, to become one of the rare stories that does not end at the first serious blow.

12. Synthesis: Is the Impact Clock Enough to Explain the Silence?

By this point, the impact clock has gone from a metaphor to a full-blown hypothesis: impacts as a stochastic reset process, technological ascent and escape as competing tempos, and a galaxy that may be full of intelligent species whose technospheres are intermittent, fragile, and often erased. The natural closing question is blunt: is that enough? Could impact-driven resets, by themselves, plausibly explain why the sky appears quiet? Or are we better off treating impacts as one important filter among many, rather than the filter?

This section gathers the threads. First, it restates the impact clock hypothesis in Fermi-paradox language. Second, it sketches the extreme parameter regime in which impacts alone could, in principle, generate a quiet galaxy. Third, it argues that, given what we know and don't know, the more reasonable stance is that impacts are probably a major factor but unlikely to be the sole explanation. Finally, it points to open questions in astrobiology, risk science, and long-term strategy that could either strengthen or weaken the impact clock's claim to centrality.

12.1 Summarizing the impact clock hypothesis in Fermi terms

The Fermi Paradox begins with an apparent mismatch: a vast, old galaxy that seemingly offers many opportunities for life and intelligence to arise, and a current observational situation in which we do not see obvious signs of galactic-scale civilizations. The impact clock hypothesis offers a particular way to dissolve part of this mismatch. In its simplest form, it can be summarized in four steps.

First, technological civilizations are inherently fragile in their early phases. Before they become multi-planetary or deeply hardened, their infrastructure and knowledge are concentrated in thin surface layers, vulnerable to large-scale disruption.

Second, impacts provide a recurrent, mostly random set of disruptions. For Earth-like worlds, small and medium-sized impactors arrive with frequencies measured in centuries to tens of thousands of years, and sub-Chicxulub catastrophes arrive on longer but still finite timescales. These events are energetic enough to erase cities and collapse global infrastructure without necessarily extinguishing the species.

Third, the timescales for technological ascent and escape are comparable to, but not necessarily shorter than, the recurrence times of civilization-resetting impacts. That is, there is no guarantee that a species will build robust, multi-planetary resilience before the next serious blow.

Fourth, when ascent and escape are repeatedly interrupted by impacts, a planet's history is carved into many short technological episodes separated by longer quiet intervals. The duty cycle of technosignatures becomes low: at any randomly chosen time, even a planet with multiple past civilizations is likely to appear pre-technological or only modestly advanced.

Translated into Fermi language: the galaxy may not lack for intelligent life, or even for civilizations that occasionally reach radio and rockets. But because impact clocks (and other hazards) keep most worlds in the “intermittently loud” regime rather than the robust regime, the fraction of time during which any given inhabited world is detectable is very small. When we look out, we are mostly seeing worlds in the wrong phase of their cycle.

12.2 Conditions under which impact resets alone could yield a quiet galaxy

For impacts alone to bear the full explanatory weight of the observed silence, several conditions would need to hold simultaneously, and fairly strongly, across a large fraction of habitable worlds. At least three are central.

First, impact rates at the relevant energies would need to be high enough, on most Earth-like planets, to disrupt technological ascent repeatedly. That means not only rare Chicxulub-class events over hundreds of millions of years, but also more frequent sub-Chicxulub and city-killer events on timescales of tens of thousands of years or less. These would need to be sufficiently common that the probability of uninterrupted, multi-millennial radio-loud phases is low unless planetary defense is achieved quickly.

Second, the typical ascent clock would need to be long enough, and the typical escape clock longer still, that few civilizations manage to traverse the gap from radio-loud vulnerability to robust multi-planetary safety before an impact-driven reset occurs. If ascent were extremely fast and escape relatively easy—say, if species routinely went from first radios to robust off-world colonies in a few centuries—then even fairly active impact clocks might not suffice to keep the galaxy quiet. The hypothesis leans on the idea that building resilience takes substantial time and coordination, and that this window is often cut short.

Third, the distribution of system architectures would need to be such that “impact-hot” environments are common. If, instead, most habitable worlds orbit stars in unusually clean, quiet small-body environments, then the impact clock would be too slow to dominate. In that case, other filters—self-inflicted, cultural, astrophysical—would have to carry more of the explanatory load. For impact resets alone to do the job, a significant fraction of life-bearing

planets would have to experience recurrent mid-scale bombardment through much of their habitable lifetimes.

Under these conditions, a purely impact-driven explanation becomes plausible. Civilizations flare up often enough to be common in a time-integrated sense, but rarely stay alight long enough, or spread far enough, to build obvious large-scale technosignatures. Silence at any given moment is then exactly what we should expect.

12.3 Why “probably a major factor” is more plausible than “sole explanation”

However, it is one thing to identify a regime in which impacts could, by themselves, explain silence, and another to argue that this is the regime our galaxy actually occupies. Several considerations suggest caution and favor a more modest conclusion: that impacts are likely part of the story, perhaps a large part, but not the whole story.

First, impact climatology is only one source of exogenous hazard. Other astrophysical filters—flares, supernovae, gamma-ray bursts, long-term stellar evolution—also shape habitability and civilizational risk, sometimes on comparable timescales. Ignoring them would artificially concentrate causal weight on impacts alone. In reality, a civilization’s hazard landscape is multi-dimensional; impacts occupy one axis.

Second, self-inflicted filters are too tightly woven into technological capability to dismiss. Once a species can deploy nuclear weapons, engineer pathogens, or create powerful autonomous systems, the probability of internally generated catastrophes is non-negligible. Even in a universe with no impacts at all, many civilizations might still truncate their own radio-loud phases through war, environmental collapse, or runaway technologies. Conversely, some might navigate these risks successfully even in impact-prone systems. The observed silence is almost certainly a joint outcome of both external and internal dynamics.

Third, cultural filters introduce real variation in how civilizations respond to both internal and external risks. Even at identical impact rates, one species might embrace planetary defense and off-world expansion, while another rejects such projects for ethical, religious, or philosophical reasons. A third might divert most of its energy into inward-facing pursuits, deliberately minimizing technosignatures. The impact clock interacts with these choices but does not determine them. A purely impact-centric explanation would fail to capture this diversity.

Fourth, our empirical base is thin. We have detailed data for one planetary system and almost no direct observations of technological activity elsewhere. The same uncertainty that permits impact clocks to loom large also leaves room for many other filters. In such a context, declaring impacts the sole or dominant explanation for silence would be premature. A more intellectually honest stance is to treat them as a well-motivated ingredient in a broader, still-speculative mixture.

Put differently: the impact clock hypothesis is strong enough to challenge naive assumptions that “once radio, always visible,” but not strong enough, on current evidence, to exclude other filters. The most reasonable position is that impacts probably contribute significantly to keeping many worlds in the quiet or intermittently loud regimes, but that self-inflicted risks, astrophysical hazards, and cultural choices almost certainly modulate, reinforce, or sometimes outweigh this effect.

12.4 Open questions for astrobiology, risk science, and long-term strategy

If impacts are to move from plausible story to quantitative factor, several lines of inquiry will matter. They span disciplines: astrobiology, planetary science, risk analysis, and the ethics and strategy of long-term civilization.

For astrobiology and planetary science, a key task is to refine impact climatology across system types. How do impact rates vary with stellar class, planetary architecture, and small-body reservoir structure? Are Earth’s impact rates typical, high, or low? Can we, in time, infer impact histories indirectly from exoplanet observations—for example, through crater statistics on resolved surfaces, debris disk morphologies, or atmospheric signatures of past bombardments? Better constraints here would narrow the plausible parameter space for the impact clock.

In risk science, the challenge is to connect physical hazard models with civilizational dynamics. What levels of infrastructural robustness render city-killer impacts non-resetting? How do compound risks—impacts plus climate stress, or impacts plus conflict—alter collapse probabilities? Can we build realistic agent-based or system-dynamics models that simulate not just single shocks but centuries-long sequences of stress and adaptation? These questions sit at the intersection of catastrophe modeling, complex systems, and social science.

For long-term strategy, the impact clock picture reframes priority-setting. It suggests that planetary defense and resilience are not niche pursuits but central components of any civilization that hopes to cross key Great Filters. It raises practical questions: What fraction of resources should be devoted to impact detection and deflection relative to other global risks? How can institutions be structured to maintain vigilance over timescales longer than any one generation’s attention span? What forms of off-world infrastructure offer the best trade-off between early feasibility and long-term robustness?

Finally, for the philosophy of SETI and cosmic sociology, the impact clock invites a broader repertoire of expectations. Rather than assuming a sharp dichotomy between “no one is out there” and “someone should already be everywhere,” we may need to think in terms of a spectrum of civilizational duty cycles, many of them low. This leads naturally to new search strategies: looking for transient and archaeological technosignatures, for statistical anomalies in

exoplanet atmospheres, or for local traces of previous technological cycles within our own system.

In closing, the impact clock is best understood not as a complete answer to the Fermi Paradox, but as a lens. It brings into focus one particular way in which physical randomness and civilizational fragility can interact to produce a stone-age galaxy: full of minds, short on enduring machines. Whether that lens captures most of the truth or only a slice of it remains an open question—one that future observations, models, and our own strategic choices will help to clarify.

13. References

13.1 Impact physics, crater statistics, and extinction literature

1. Alvarez, L. W., Alvarez, W., Asaro, F., & Michel, H. V. (1980). Extraterrestrial cause for the Cretaceous–Tertiary extinction. *Science*, 208(4448), 1095–1108.
2. Melosh, H. J. (1989). *Impact Cratering: A Geologic Process*. Oxford University Press.
3. Bottke, W. F., Cellino, A., Paolicchi, P., & Binzel, R. P. (Eds.). (2002). *Asteroids III*. University of Arizona Press.
4. Chapman, C. R., & Morrison, D. (1994). Impacts on the Earth by asteroids and comets: assessing the hazard. *Nature*, 367, 33–40.
5. Toon, O. B., Zahnle, K., Morrison, D., Turco, R. P., & Covey, C. (1997). Environmental perturbations caused by the impacts of asteroids and comets. *Reviews of Geophysics*, 35(1), 41–78.
6. Schulte, P., et al. (2010). The Chicxulub asteroid impact and mass extinction at the Cretaceous–Paleogene boundary. *Science*, 327(5970), 1214–1218.
7. Collins, G. S., Melosh, H. J., & Marcus, R. A. (2005). Earth Impact Effects Program: A web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth. *Meteoritics & Planetary Science*, 40(6), 817–840.
8. Kring, D. A. (2007). The Chicxulub impact event and its environmental consequences at the Cretaceous–Tertiary boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 255(1–2), 4–21.
9. Raup, D. M., & Sepkoski, J. J. (1984). Periodicity of extinctions in the geologic past. *Proceedings of the National Academy of Sciences USA*, 81(3), 801–805.
10. Zahnle, K., Dones, L., & Levison, H. F. (1998). Cratering rates on the Galilean satellites. *Icarus*, 136(2), 202–222.

13.2 Fermi Paradox, Great Filter, and SETI frameworks

11. Fermi, E. (1950). Unpublished remark during lunch discussion at Los Alamos; summarized in: Jones, E. M. (1985). Fermi’s question, “Where is everybody?”. *Los Alamos National Laboratory Report LA-10311-MS*.
12. Brin, G. D. (1983). The ‘Great Silence’: the controversy concerning extraterrestrial intelligent life. *Quarterly Journal of the Royal Astronomical Society*, 24, 283–309.
13. Hart, M. H. (1975). Explanation for the absence of extraterrestrials on Earth. *Quarterly Journal of the Royal Astronomical Society*, 16, 128–135.

14. Tipler, F. J. (1980). Extraterrestrial intelligent beings do not exist. *Quarterly Journal of the Royal Astronomical Society*, 21, 267–281.
15. Hanson, R. (1998). The Great Filter—Are we almost past it? Online essay, later anthologized in discussions of the Fermi Paradox.
16. Ćirković, M. M. (2004). The temporal aspect of the Drake equation and SETI. *Astrobiology*, 4(2), 225–231.
17. Webb, S. (2015). *If the Universe Is Teeming with Aliens... Where Is Everybody?* (2nd ed.). Springer.
18. Wright, J. T. (2020). Strategies and advice for the search for extraterrestrial technosignatures. *Acta Astronautica*, 168, 52–68.
19. Lingam, M., & Loeb, A. (2021). *Life in the Cosmos: From Biosignatures to Technosignatures*. Harvard University Press.
20. Balbi, A. (2020). *The Silence of the Universe: Why We Haven't Detected Extraterrestrial Life—Yet*. Harvard University Press.

13.3 Models of collapse, resilience, and technological vulnerability

21. Tainter, J. A. (1988). *The Collapse of Complex Societies*. Cambridge University Press.
22. Diamond, J. (2005). *Collapse: How Societies Choose to Fail or Succeed*. Viking.
23. Homer-Dixon, T. (2006). *The Upside of Down: Catastrophe, Creativity, and the Renewal of Civilization*. Island Press.
24. Motesharrei, S., Rivas, J., & Kalnay, E. (2014). Human and nature dynamics (HANDY): Modeling inequality and use of resources in the collapse or sustainability of societies. *Ecological Economics*, 101, 90–102.
25. Bostrom, N. (2013). Existential risks: analyzing human extinction scenarios and related hazards. *Journal of Evolution and Technology*, 9(1), 1–31.
26. Ord, T. (2020). *The Precipice: Existential Risk and the Future of Humanity*. Bloomsbury.
27. Rees, M. (2003). *Our Final Century* (also published as *Our Final Hour*). Arrow Books.
28. Galaz, V., et al. (2014). Global environmental governance and planetary boundaries: An introduction. *Ecology and Society*, 19(4), 1–7.
29. Scheffer, M., et al. (2012). Anticipating critical transitions. *Science*, 338(6105), 344–348.
30. Helbing, D. (2013). Globally networked risks and how to respond. *Nature*, 497(7447), 51–59.

13.4 Ethical, philosophical, and policy treatments of planetary defense

31. Morrison, D., Harris, A. W., Sommer, G., Chapman, C. R., & Carusi, A. (2002). Dealing with the impact hazard. In W. F. Bottke et al. (Eds.), *Asteroids III* (pp. 739–754). University of Arizona Press.
32. National Research Council. (2010). *Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies*. The National Academies Press.
33. Schweickart, R. L., Chapman, C. R., Durda, D. D., & Hut, P. (2008). Threat mitigation: the

- gravity tractor. In *Asteroids, Comets, Meteors 2008* (LPI Contribution No. 1405).
34. Cockell, C. (2008). The ethical value of information in the context of planetary protection. *International Journal of Astrobiology*, 7(3–4), 223–230.
35. Impey, C., Spitz, A. H., & Stoeger, W. R. (2013). *Encountering Life in the Universe: Ethical Foundations and Social Implications of Astrobiology*. University of Arizona Press.
36. Persson, E., & Holm, S. (Eds.). (2017). *Planetary Defense: Global Collaboration for Defending Earth from Asteroids and Comets* (selected conference papers and policy discussions).
37. United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS). Various years. Reports of the Action Team on Near-Earth Objects and the International Asteroid Warning Network.
38. NASA Planetary Defense Coordination Office. Ongoing. Program documentation and strategic plans for near-Earth object detection and mitigation.
39. Jones, R. A. (2018). Space ethics: The final frontier of responsible space exploration and use. *Space Policy*, 45, 9–17.
40. Crawford, I. A. (2016). Space exploration and humanity's future: philosophical and ethical perspectives. *Acta Astronautica*, 126, 263–267.

The author has published over 4,600 AI-assisted papers at:

<https://www.researchgate.net/profile/Douglas-Youvan/research> . Google Scholar has indexed these preprints, and if you want a particular reference, the AI mode of a Google search (Gemini) has efficiently catalogued these preprints.